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SOME EXPERIMENTS ON THE MEASUREMENT OF NATURAL ICE NUCLEI[1]

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ABSTRACT

A brief description is given of a new refrigerated expansion chamber apparatus based on an Australian C.S.I.R.O. design for measuring ice nuclei concentrations. The compatibility of results between five instruments of similar construction, a comparison of data obtained with a simple version of the mixing chamber method, and homogeneity of rapid expansion measurements at sites 8 and 100 miles apart are investigated. Except for uncertainties regarding the extrapolation of results to natural clouds, all indications are that, with care, the nucleation level in the atmosphere is capable of objective, compatible measurement with standardized equipment. However, a series of measurements verified the existence of significant differences between the rapid expansion and mixing chamber techniques. Both methods reflected similar trends during appreciable increases or decreases in nucleation activity. A surprisingly uniform geographical distribution of aerosols responsible for ice crystal nucleation is suggested in some of the results.

1. INTRODUCTION

The microphysical processes involved in the water-to-ice transformation in supercooled clouds has received increasing attention in recent years. It is generally accepted that one of the critical factors is the concentration of certain kinds of comparatively rare particles suspended in the atmosphere which serve as nucleating agents. This particular class of particles is variously referred to in the literature as "freezing," "sublimation," "deposition," or "ice" nuclei, depending on the physical mechanisms invoked. The more general nomenclature of "ice nuclei" is used here in view of the current uncertainties as to the exact physical nature of the process.

Since those particles under consideration normally constitute only an extremely minute fraction of the total atmospheric aerosol population, their detection on a routine basis at the present time requires the use of refrigerated devices and the production of supercooled droplets and ice crystals under what must be inferred as highly artificial circumstances in the light of the scale of events in natural clouds. The a priori assumption is that the concentration of ice crystals produced in a given volume of air is a measure of the number of ice nuclei present which are active at temperatures between some threshold value and the particular cloud-chamber temperature at which the observations are obtained. The temperature dependency is extremely critical and somewhat variable; a 2° to 5° C. change results in roughly an order of magnitude difference in the number of particles activated.

While the basic assumption mentioned above appears valid, it is also an over-simplification in the sense that the ice nucleation process is known or suspected to involve subtle and delicate interactions of such additional parameters as instantaneous supersaturation levels, nuclei size, and droplet volume, along with crystallographic and surface properties of the nuclei. Nor is it yet entirely clear whether these nuclei participate directly in the condensation process, or are activated mainly by coagulation with the exterior surfaces of pre-existing cloud droplets, or possibly by deposition of moisture directly from the vapor state.

[1] These results were obtained in connection with an investigation sponsored jointly by the National Science Foundation (under NSF-GL29) and the U.S. Weather Bureau.

As a consequence of the complex nature of the problem and the present status of instrumentation in the field, it has seemed appropriate to adopt an inquiring attitude on the question of the measurability of ice nuclei concentrations in the free atmosphere. The main purpose of this paper is to summarize the results of a series of experiments designed to partially assess this problem, and incidentally, to describe an instrument which has now been in field service in multiple numbers over a sufficient period of time to be able to report an acceptable level of mechanical integrity and durability.

Although a modest number of ice nuclei measurements has been made in recent years, it has proved exceedingly difficult to evaluate or synthesize the data. Uncertainties exist regarding the compatability of instruments and measuring techniques, sampling variations in the atmosphere as they reflect on the representativeness of such observations, as well as regarding the knowledgeable interpretation of cold box data as precise and meaningful cloud physics measurements. The absence of an absolute measuring technique requires that judgments of the reliability of such measurements must be, for the time being, based largely on evaluations of the internal consistency of such data.

The results presented here appear to contribute constructive and hitherto missing or sketchy information with respect to the confidence assignable to such measurements beyond a laboratory environment, along with indications of the compatibility of two methods most widely used to date. However, it must be emphasized that a large number of important questions on the interpretation of such measurements remains to be answered.

A discussion of the relationships of these and other daily measurements to meteorological events will be presented later. Some early and rather unexpected experimental results and synoptic clues pointing toward a potentially significant natural source of ice nuclei, utilizing the equipment described here, have been reported by Brier and Kline [1], Kline [2], and Battan and Riley [3]. Most of the measurements discussed in this paper were obtained in and around the Washington, D.C. area in conjunction with an observational program now in progress at a number of widely separated locations during selected periods with the assistance of a number of cooperating organizations. Although these data reflect the results of an evaluation of two particular techniques, the much broader objective of assessing the reliability of such measurements in the free atmosphere strongly motivated this study.

2. EQUIPMENT

An external view of one of the identically constructed instruments used in this investigation is shown in figure 1. The equipment is an adaptation of the basic design described by Warner [4]. The essential components enclosed in the console consist of: (1) a 10-liter insulated copper cylinder with the wall and bottom external surfaces

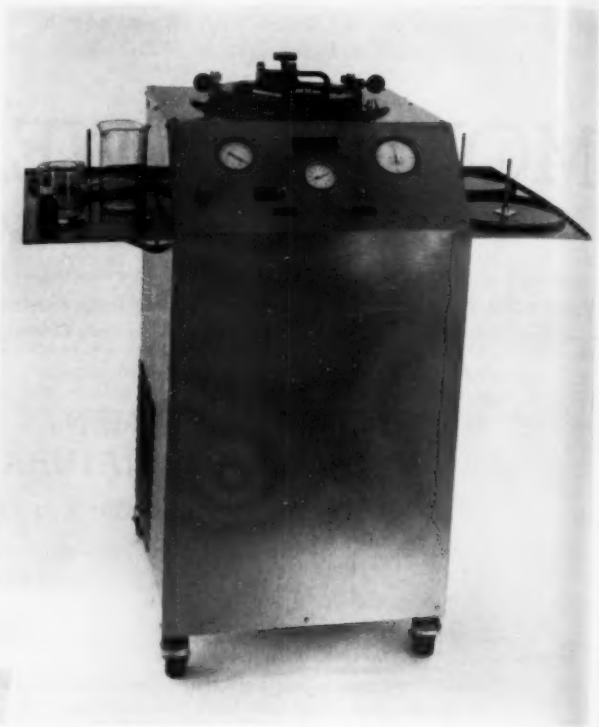

FIGURE 1.—Refrigerated expansion cloud chamber (Experimental Bigg-Warner Type) developed by U.S. Weather Bureau as a modified version of an original design by the Australian Commonwealth Scientific and Industrial Research Organization.

surrounded by copper tubing functioning as the evaporator in the refrigeration system, (2) a 1/3 h.p. hermetically sealed Freon 22 (b.p.—40.5° C.) compressor unit with a fan-cooled condenser, and (3) a 1/4 h.p. rotary air pump of 200 c.f.m. maximum capacity for pressurization of the chamber. Orifices flush with the inside chamber wall are vented to a sensitive differential pressure gage (modified air speed indicator) and the air pump. The latter is connected to a standard rubber air hose at the rear of the console. The dial of the air speed indicator is calibrated to indicate a temperature drop on expansion equivalent to the theoretical wet adiabatic value. The wall temperature indicator is a conventional dial-type bi-metallic thermometer in thermal contact with the exterior of the copper chamber about 1/3 of the distance from the bottom to the top of the chamber. The air seal is maintained between the Plexiglas lid and the chamber by adjustable clamps and a Neoprene O-ring. Decompression resulting in supercooled fog formation is accomplished by opening a spring-loaded valve in the lid after precooling of each air sample. Check and relief valves are installed in the air intake system to retain pressure between the pump and chamber and to prevent over-pressurization resulting in damage to the temperature calibrated pressure gage. The expansion

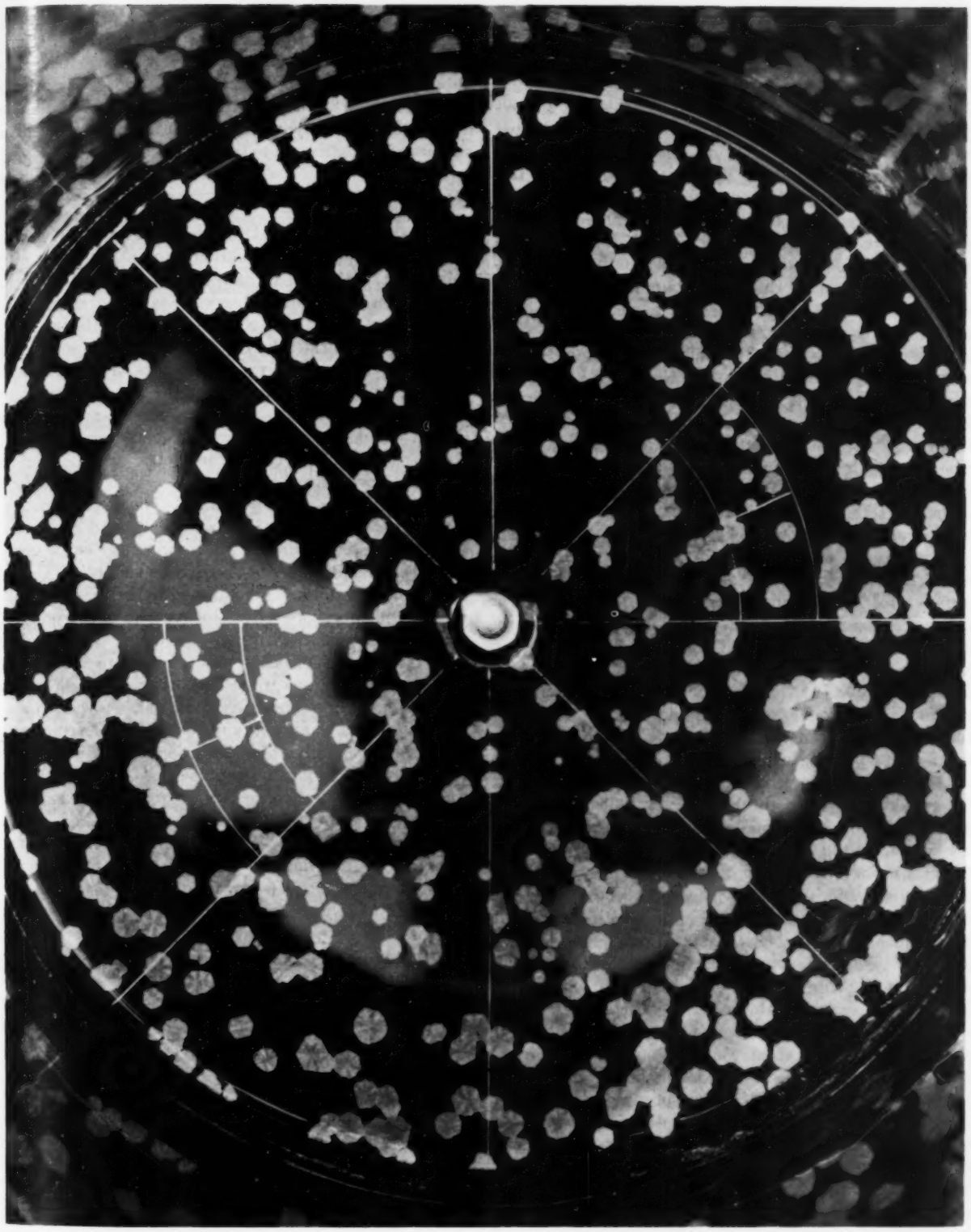

FIGURE 2.—Example of ice crystals produced in a removable tray containing a supercooled sugar solution and placed on the bottom of the cloud chamber. This photograph was obtained with a camera mounted at the top of the chamber.

ratios used in normal operation are approximately 1.08, 1.17, 1.26, and 1.37 for observations at −15° C., −20° C., −25° C., and −30° C., respectively, depending on the wall temperature.

Special attention was directed to the problem of achieving stable wall temperature control. The system adopted for primary use relies entirely on a manually adjustable automatic expansion valve. This valve serves in practice to meter only a sufficient amount of liquid Freon 22 to the cooling coils to maintain a constant evaporation pressure. Manual adjustment is required to compensate for the heat load imposed by ambient temperature conditions. The pressure differential across the expansion valve is monitored by reference to a vacuum pressure gage located on the front panel of the console. The compressor remains in continuous operation, with this control system thus eliminating the temperature instability problems inherent in the conventional thermostatically controlled on-and-off cycling methods. Provisions for the latter system are included, however, where the equipment must be used in ambient temperature conditions below which the refrigerant cannot be metered in sufficiently small amounts to prevent damage to the compressor due to back-pressure.

Thermocouple surveys on two units operated at the normal wall temperature of −10° C. indicated a uniform temperature distribution (within 0.3° C.) over the lower 2/3 of the chamber with an inversion of the order of 10° C. extending through the top 4 inches, depending on the temperature differential between the wall and outside environment. Although introducing some uncertainty on the "effective" sampling volume, a temperature inversion is an essential feature of the expansion technique to provide a reservoir of water vapor for reliable supercooled fog production at low expansion ratios. Measurements of temperature recovery times of the wall and bottom surfaces following purging with air at 23° C. were all within the range of 90 to 130 seconds, depending on the duration of the flushing cycle.

Three particularly attractive features characterize the expansion technique. One is the ease with which the sugar solution method developed by Bigg [5] may be used for objective detection and counting of the ice crystals produced in the entire 10-liter sampling volume, as shown in figure 2. Second is the rapidity of sampling over a spectrum of temperatures through controlled variations in the overpressure; and third, a normal operating wall temperature of −10° C. to −12° C. which considerably reduces the risks of contamination from splintering and fragmentation of frost particles on refrigerated surfaces over those encountered under humid conditions at colder wall temperatures. Glycerin is used as a freezing point depressant through careful coating of the walls of the copper chamber to prevent frost formation. The present version of the equipment was deliberately "over-designed" with respect to compressor capacity to provide both quick cooling capabilities (under 10 minutes from 30° C. to normal operating levels) and optional use at colder wall temperatures for test with the mixing chamber method. Supercooled cloud temperatures as low as −30° C. can be obtained either by the expansion process or by selective changes in the wall temperature by means of the adjustable refrigeration expansion valve in the case of the mixing chamber method.[2]

3. PROCEDURES

The approach adopted for this investigation was dictated by considerations involving the intended use of the equipment. Most of the data were obtained during the course of a twice-daily observational program with the instruments used under conditions representative of field operation. In principle, greater precision in some of the results should be achievable in laboratory environment. However, possible influences on the results by different operating procedures, sampling variations, and uncertainties on the nature of the aerosols characterizing those in the free atmosphere were all considered potentially critical factors in evaluating the confidence which could be assigned to such measurements. The equipment was located out-of-doors or in a well ventilated enclosure at all times to assure purging with representative air samples by several rapid up-and-down movements of the tray within the chamber. Flushing with the air pump alone was found unreliable due to particle scavenging and problems associated with non-uniformity of airflow inside the chamber. Replication procedures were used throughout the measuring program. Efforts were made to obtain a minimum of five consecutive runs in the case of measurements confined to a single supercooled-cloud temperature, or a sufficient number of observations at varying temperatures to define a mean temperature-spectrum-concentration curve. A "reference temperature" of −20° C. was adopted for all observations confined to a single value.

The reproducibility of ice nuclei measurements between instruments (designated by manufacturer's serial number in the discussion to follow) was examined by simultaneous operation of two units located side-by-side. One of the instruments (No. 3) was retained as a "reference" unit throughout the test series, the choice being entirely arbitrary. Efforts were made to cover a representative range of ice nuclei concentrations to compare both the mean value and parallelism in the trends. Each unit was frequently operated by different observers with the ice crystal counts being made independently.

An examination of the areal representativeness of expansion measurements was made in connection with twice daily measurements at two fixed sites. One instrument was located on the roof of an office building approximately 130 feet above the street level in downtown Washington, D.C. A second unit was operated in a suburban resi-

[2] The term "mixing chamber method" is usually applied to techniques in which the wall temperature is maintained at a quasi-steady value. The air samples are allowed gradually to reach thermal equilibrium with the refrigerated surfaces. A supercooled cloud is usually produced by introducing moisture into the chamber from an external source.

dential section about 8 miles west of the metropolitan area. The downtown observations were normally made during the morning between 0900 and 1030 EST and during the afternoon between 1500 and 1630 EST. The normal observation times for the second series were 0530 to 0700 and 1830 to 2000 EST. A subsequent more limited comparative series was obtained between downtown Washington, D.C. and the U.S. Coast Guard Indian River Inlet Lifeboat Station located approximately 100 miles due east of Washington. These observations were performed at predetermined schedules during mid-forenoon and mid-afternoon periods and included measurements over a spectrum of temperatures in all instances.

In the case of the comparative runs between the expansion and mixing chamber techniques, the following procedure was adopted: A series of five expansion runs at −20° C. with different air samples was made with the wall temperature maintained at −10° C. (±0.5° C.). Immediately following the expansion series, the wall temperature was cooled to −20° C. for a similar number of measurements with the mixing chamber method. Two cloud chambers were used for the latter series. One was operated at a temperature of −5° C. for precooling the sugar solution, thus permitting nearly instantaneous response to any ice crystals produced in the second chamber after purging and insertion of the cooled tray. Counts with the latter method were made at 1- and 2-minute intervals. Two minutes represented about the maximum upper limit practicable with this method due to parasitic wall frost problems, unreliable fog duration over longer periods, and merging of the growing crystals. Each complete set of sequential measurements in this test series spanned periods ranging from 60 to 120 minutes, depending on difficulties with contaminating frost. These experiments were conducted under summer temperature and humidity conditions such that a supercooled fog formed spontaneously in each fresh air sample drawn into the chamber when operated at −20° C. for the mixing chamber measurements, thus eliminating a need for the exhalation method or other more elaborate procedures for producing supercooled droplets. The sugar solution used at −10° C. consisted of equal parts of water and sugar by weight plus a wetting agent to reduce surface tension to provide uniform coverage of the trays. This mixture was modified to a slightly more concentrated strength to delay excessive supercooling resulting in spontaneous freezing of the solution and overlapping of the ice crystals which would otherwise grow too rapidly at the colder temperature used in the mixing chamber method. The severity of the frost problem at the operating temperature of −20° C. was such that it was usually necessary to reapply glycerin to the wall surfaces after each run with the mixing chamber method. Except for those instances where the counts were obviously contaminated by wall frost, all data were used. Because of the extraordinary tediousness of the mixing chamber method under humid environmental conditions, most of these data were obtained by the same observer. The detection of ice crystals by the sugar solution technique in both methods was considered preferable to the "scintillation technique" usually used with mixing chamber method, in order to reduce sampling uncertainties.

4. RESULTS

(a) *Compatibility between instruments.*—A total of 89 sets of simultaneous runs using 5 instruments in pairs was performed on 61 days. Although a majority of the runs were confined to replicated observations at −20° C., a few series included temperature-spectrum measurements. Four representative examples of the latter runs with two units are shown in figure 3. A graphical presentation of all series obtained at −20° C. is shown in figure 4 to indicate the relationship between the readings of the "reference" unit and each of the other units tested. Of these instruments, units No. 4 and 5 displayed the widest difference with a mean ratio with respect to the reference unit of 1.5, a statistically significant departure from unity. Unit No. 6 displayed values in somewhat closer agreement, the average ratios of all the series with this pair being 1.3. The comparative series with unit No. 1 gave a ratio of 0.8, a statistically significant discrepancy. Correlation coefficients between the paired series ranged from 0.95 to 0.99. The differences between units were therefore assumed to reflect a systematic bias, as is obvious from inspection of figure 4.

(b) *Comparison of rapid expansion and mixing chamber methods.*—This test series included 142 sets of observations on 74 days. The results corresponding to the 2-minute intervals are shown as a scatter diagram in figure 5 with each data point representing the average of the counts obtained in each sequential set of observations. The mathematically fitted regression has significant curvilinearity and indicates that both methods tend to give about the same average number of ice crystals only at higher concentration levels. However, the rare occurrence of extreme concentrations and counting difficulties introduces some degree of uncertainty in the location of the regression curve in this area. The correlation coefficient between the rapid expansion counts and the 2-minute mixing chamber values was 0.77. Overall, 2-minute mixing chamber counts at −20° C. were 6.8 times the rapid expansion values, but the ratios varied appreciably over the concentration range as shown by the regression curve in figure 5. An examination of the trends in mean values between consecutive sets of observations revealed that when the rapid expansion counts increased or decreased by a factor of 2 (70 cases), the trends in the mixing chamber measurements were in the same direction in 83 percent of the cases. Changes by a factor of 4 or greater (22 cases) resulted in both techniques reflecting parallel changes in all instances. In an analysis of variance, both techniques showed highly significant differences between the means of sets of obser-

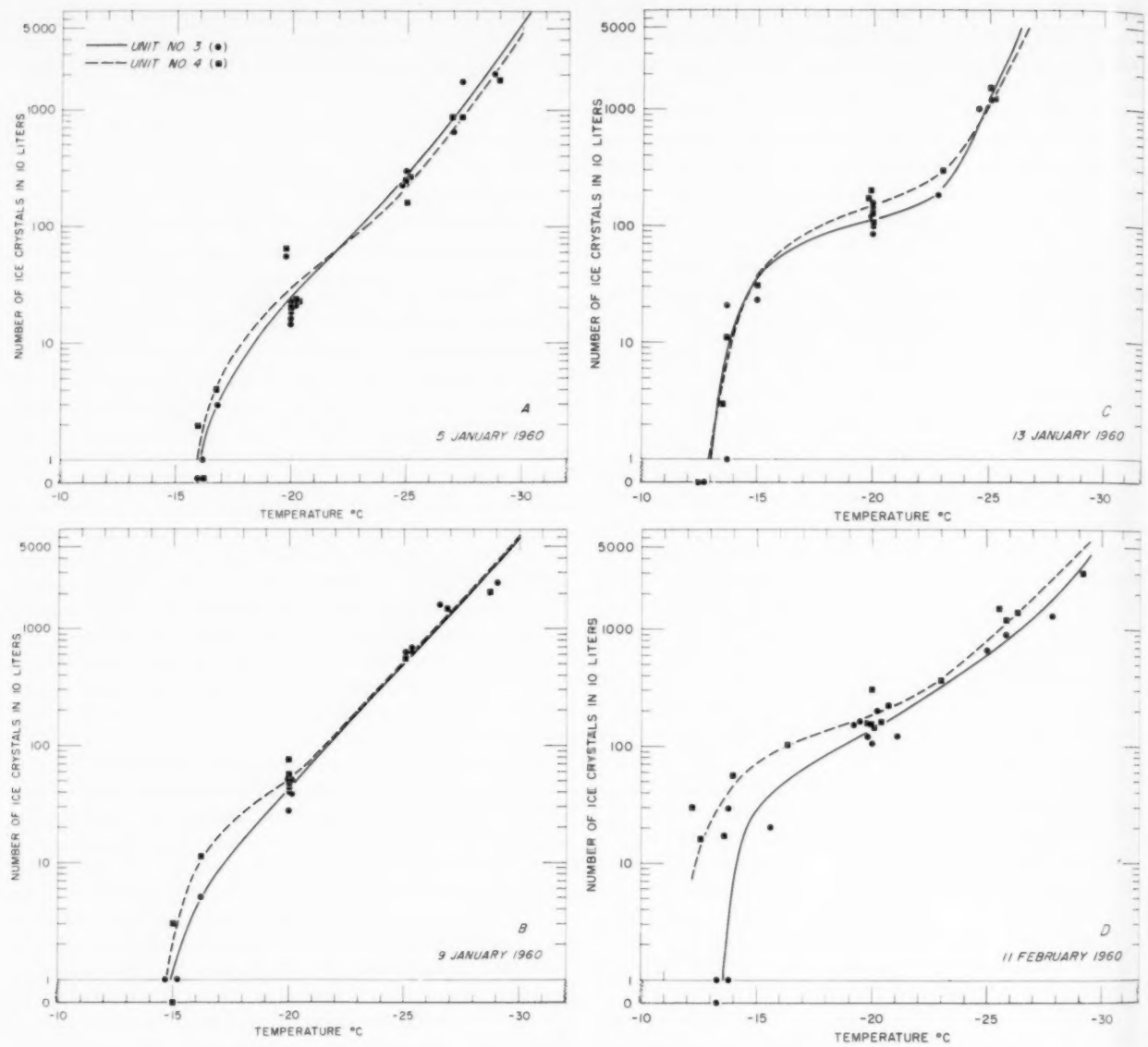

FIGURE 3.—Examples of nuclei temperature-spectrum concentrations obtained during simultaneous operation of two expansion cloud chambers. (a) January 5, 1960; (b) January 9, 1960; (c) January 13, 1960; (d) February 11, 1960.

vations, indicating that the variations of nuclei counts with time are real and much larger than the experimental "error."

If the counts obtained by the rapid expansion method are compared with the 1-minute mixing chamber counts (not given here) a correlation of 0.75 results, which is not much different than the correlation of 0.77 between the expansion chamber counts and the 2-minute interval counts. The correlation between the 1-minute interval counts and 2-minute interval counts was 0.84. This indicates that a large portion ($0.84^2=71$ percent) of the variation in the counts at 2-minute intervals can be explained in terms of values at 1 minute. When the counts were relatively high at the end of the 2-minute intervals there was a slight but statistically significant tendency ($r=0.23$) for a higher percentage of the crystals to appear during the first minute.

Another series of measurements data with a different instrument made over a spectrum of temperatures during low concentrations on six different days is shown in figure 6. These data were obtained by a continuous fog generation method using a 15-watt light bulb surrounded by a moist fabric and suspended in the center of the chamber, a method described by Soulage [6]. The sugar solution

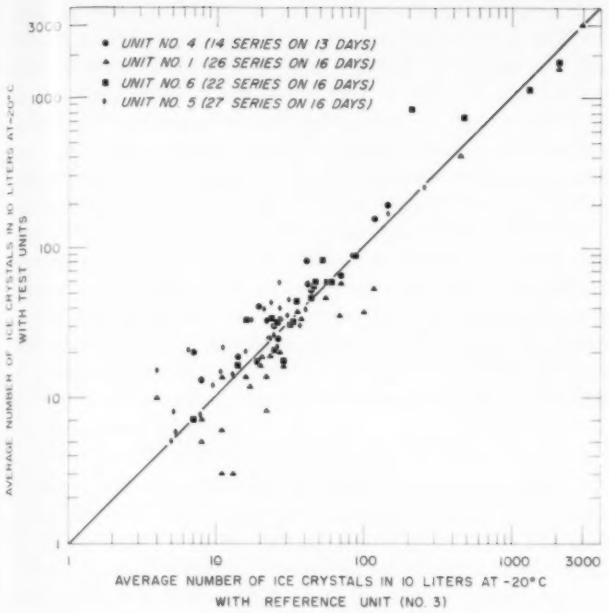
UNIT NO. 4 (14 SERIES ON 13 DAYS)
UNIT NO. 1 (26 SERIES ON 16 DAYS)
UNIT NO. 6 (22 SERIES ON 16 DAYS)
UNIT NO. 5 (27 SERIES ON 16 DAYS)
AVERAGE NUMBER OF ICE CRYSTALS IN 10 LITERS AT -20°C WITH TEST UNITS
AVERAGE NUMBER OF ICE CRYSTALS IN 10 LITERS AT -20°C WITH REFERENCE UNIT (NO. 3)

FIGURE 4.—Results of simultaneous expansion measurements at −20° C. obtained with five units, one of which was used throughout the tests as a "control" or "reference" instrument.

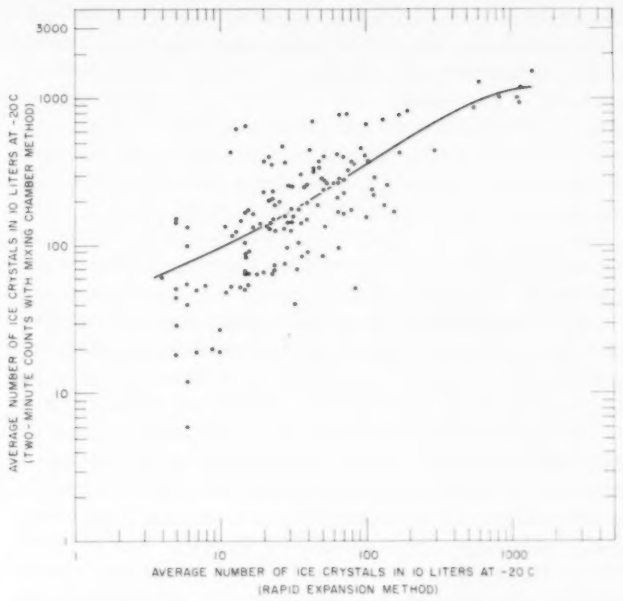
AVERAGE NUMBER OF ICE CRYSTALS IN 10 LITERS AT -20 C (TWO-MINUTE COUNTS WITH MIXING CHAMBER METHOD)
AVERAGE NUMBER OF ICE CRYSTALS IN 10 LITERS AT -20 C (RAPID EXPANSION METHOD)

FIGURE 5.—Results of sequential runs using the rapid expansion and mixing chamber techniques at −20° C. Each data point is the average of at least five consecutive samples with each method.

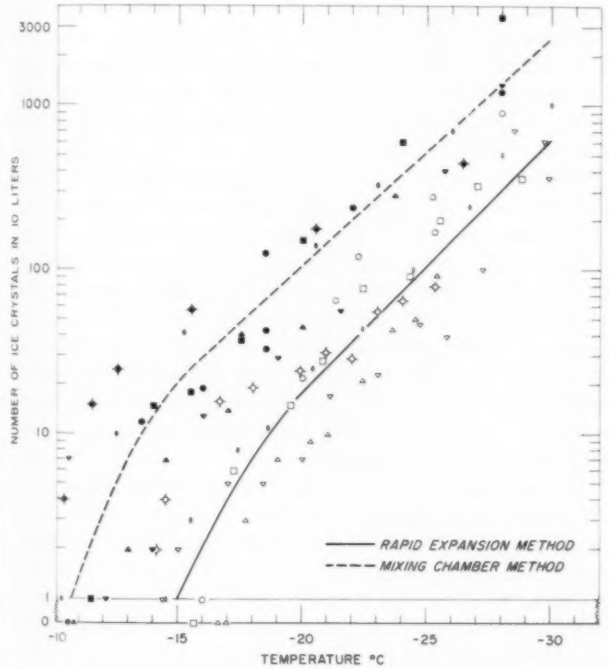

FIGURE 6.—Comparison of rapid expansion and mixing chamber measurements over a spectrum of temperatures on six different days. Data points applicable to the same series are indicated by similiar geometric configurations.

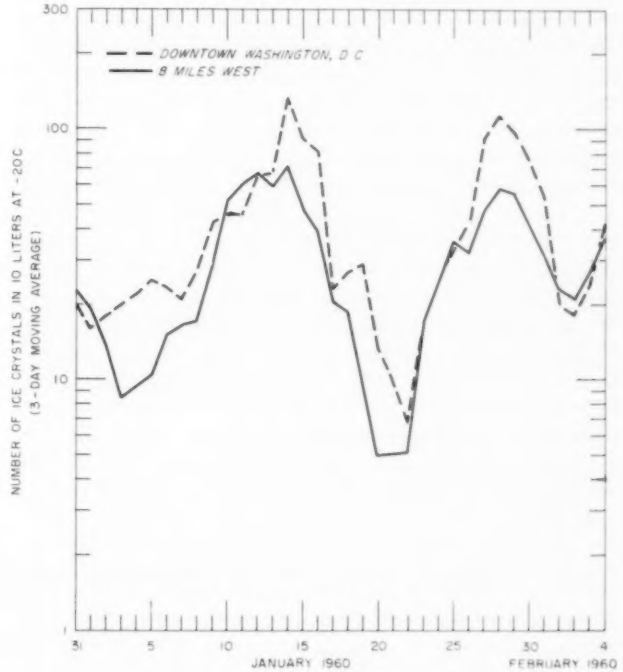
DOWNTOWN WASHINGTON, D C
8 MILES WEST
NUMBER OF ICE CRYSTALS IN 10 LITERS AT -20C (3-DAY MOVING AVERAGE)
JANUARY 1960
FEBRUARY 1960

FIGURE 7.—Comparision of ice nuclei measurements at two sites separated by approximately 8 miles.

was diluted with increasing amounts of glycerin to forestall spontaneous freezing at colder temperatures. Counts were delayed until no additional crystals were observed to form. The results at —20° C. are considered in reasonable agreement with those in figure 5 (mean ratio of 5.7 compared with 6.5 for 2-minute values in the same concentration ranges), but indicate that the ratio also varies with the "reference" or fog temperature. An adjustment of the rapid expansion mean temperature-spectrum curve toward 4° to 5° C. warmer values would appear to bring the measurements into fair agreement. In the concentration range surveyed these results compare favorably with the conclusions reached from limited series of tests with several kinds of instruments as summarized by MacCready, Smith, Todd, and Beesmer [7].

(c) *Areal representativeness of ice nuclei measurements.*—The more extensive series of observations performed to evaluate the areal representativeness of ice nuclei measurements was conducted during January and early February 1960. Although considerable differences in absolute values occurred on a few days, the overall trends were similar, as indicated in figure 7, in which the data are presented as 3-day moving averages centered about the middle day. There was an apparent tendency for the highest counts to occur in the metropolitan area, the mean monthly values differing by a factor of 1.65. However, it can be shown that this is not a real but an instrumental effect. The units used for this series (Nos. 1 and 4) have not been operated side-by-side, but both were compared with unit No. 3, as shown in figure 4. When differences in the characteristics of the instruments are allowed for, the mean monthly values at the two sites separated by 8 miles differ by a factor of 1.26, with the lowest counts in the metropolitan area. The correlation coefficients in daily mean values and the 3-day moving averages shown in figure 7 were 0.71 and 0.85 respectively.

A further examination of the spatial compatibility of ice nuclei measurements was provided by a limited series of observations at the U.S. Coast Guard Indian River Inlet Lifeboat Station near the Atlantic shoreline 100 miles east of Washington, D.C. during March 1960. These data were obtained primarily for another purpose to be reported later. However, this series was coordinated with those obtained in downtown Washington, D.C., and included 18 simultaneous sets of data at both sites over the entire temperature spectrum during similar flow regimes on 13 days. These data are summarized in table 1.

TABLE 1.—*Comparison of mean values of simultaneous ice nuclei observations during similar flow regimes*

	Threshold temp. (°C.)	No. of ice crystals per 10 liters		
		−20° C.	−25° C.	−30° C.
Shoreline	−17.7	6	76	480
Washington, D.C.	−17.3	9	119	[1] 3,000

[1] Estimated.

The two units used in this series were Nos. 3 and 4. The latter was used at the Washington, D.C. site, and, as shown in figures 3 and 4, tended to indicate the higher values. When the "correction factor" of 1.5 is applied to the shoreline data it is apparent that the counts were similar in the warmer ranges of the temperature-spectrum concentrations. Unless these results are fortuitous, which seems unlikely from close inspection of the data, this indicates a surprising uniformity in the dispersion of the responsible particles. At the colder end of the spectrum, however, the discrepancy of a factor of more than 6 at —30° C. is believed considerably larger than the probable experimental error. This suggests that observations in the colder ranges may be particularly influenced by pollution from urbanized regions.

5. DISCUSSION OF RESULTS

In assessing the outcome of the experiments reported here, it is perhaps germane to point out that in some respects these tests were rather severe. The measurements were under environmental conditions representative of field usage. By design, several observers participated in the effort and many of the observations were made during meteorological conditions in which the reliable use of refrigerated devices is awkward and tedious to an extreme. Moreover, the fact that the tests were conducted in a densely populated area with the ever-present risks of contamination from domestic and other local sources conceivably introduced greater variations than might exist elsewhere.

Judgements on the quality of agreement between instruments and techniques depend, of course, on the objectives of any measuring program. Day-to-day fluctuations in ice nuclei concentrations may span up to several orders of magnitude with factors of 5 or greater not uncommon within individual sampling periods. Close inspection of the rapid expansion data indicates that fluctuations in time of the order of a factor of 2 or more in the *mean* values of replicated series were detected by all the instruments. The absolute values appear *capable* of measurement to within at least 25 percent on the average. Differences between instruments (and observers) of the order of 50 percent with respect to the "reference" unit and up to a factor of about 2 overall are indicated, however, without special attention to precise calibration of the equipment.

The results of the comparative runs between the rapid expansion and mixing chamber methods raise some potentially crucial questions on the measurability problem. Some, perhaps most, of the scatter in the results is attributable to uncontrolled factors, particularly with the latter technique. These include not only fluctuations in the aerosol population over the sampling period, but also non-uniformity in supercooled cloud density in the chamber from day to day, and small differences in the strength of the sugar solution influencing the growth rate of the ice crystals, along with the previously mentioned

problems with wall frost. Moreover, although the mixing chamber technique is sometimes referred to as a "constant temperature" method, this is far from the case in practice due to the instantaneous fog formation with the flushing of the chamber and the time required for the temperature of fresh air samples to reach that of the wall. This extends over an appreciable part of the 2-minute period in which ice crystal formation was kept under surveillance and varies depending on the temperature differential between ambient and operating levels. The mean discrepancies between the two methods, however, appear genuine. A satisfying physical interpretation of these differences is exceedingly difficult at this stage because of the elusive and contradictory nature of the evidence concerning the basic physical-chemical processes involved in nucleation phenomena.

Aside from subtle properties of the nuclei themselves, such factors as supercooled droplet size and the time dependency of the nucleation process are probable influences. The recent work reported by Hoffer [8] points to significant influences by soluble substances in depressing the freezing temperature of droplets. In general, each of these factors would operate in the direction of reducing the number of ice crystals observed in the rapid expansion method because of the smaller droplet sizes and extremely short time-intervals at which minimum temperatures are maintained compared with those characteristic of mixing chamber or similar techniques.

We are inclined to interpret our evidence as providing empirical confirmation that either of the techniques examined may be used for studying relative variations in concentration levels. The rapid expansion method was much simpler to use in practice under the prevailing experimental conditions. However, some rather elaborate variant of the mixing chamber method such as described by Bigg and Meade [9] may be necessary to place such measurements on a more physically realistic basis. The alternative would be to calibrate the expansion method against an agreed-upon standard. Our evidence on the suitability of this approach is not entirely clear. The data in figure 6 offer considerable promise in this regard. However, the convergence tendency in the higher concentration ranges noted in connection with the results shown in figure 5 hints that a lack of stability in any such calibration may be expected. The reason for this is not obvious, but the possibility exists that day-to-day differences with respect to the nature of the nucleating particles and their response to the cloud chamber characteristics may be critical factors. A similar trend has been reported by Soulage [10].

There is, of course, the basic question at this point of whether the highly artificial conditions (especially supersaturation levels) in any refrigerated devices of reasonable dimensions provide measurements directly relevant to natural cloud events. Practically no reliable information is available on this point because of the inadequacy of existing instrumentation for measuring either nuclei or ice crystal concentrations in natural clouds. Moreover, qualitative observations indicate that natural cloud nucleation may often be facilitated by the sedimentation of pre-existing ice crystals from higher cloud formations into the supercooled portions of a cloud system and possibly also by the splintering and fragmentation of freezing particles. Natural nucleation under these circumstances would be more efficient than inferred from "cold box" measurements.

There remains the difficult problem of choosing a standard reference temperature in any compatible measuring system, since the mixing chamber and similar methods are not readily adaptable to both frequent sampling and temperature spectrum measurements. We arbitrarily adopted $-20°$ C. when runs were confined to a single temperature. However, as shown in several examples by Kline [2] the mean temperature spectrum curves often undergo wide excursions in slope and shape so that measurements at any given temperature do not necessarily reflect conditions at other values. That is, high concentrations at $-20°$ C. do not always indicate abnormal values at say $-15°$ C. and warmer values. There is, however, a statistical tendency in this direction, and $-20°$ C. appears to be an adequate compromise for some purposes.

6. CONCLUDING REMARKS

These results have been presented as a contribution toward placing some of the measuring problems in better, though still incomplete, perspective. Our evidence is that there are substantial grounds for believing that compatible and representative measurements can be achieved with carefully designed instruments and with attention to procedural quality control. At the same time, these results emphasize the existence of important instrumental and sampling problems requiring consideration in the design of future equipment and standardization of measuring techniques. That the natural aerosols responsible for ice crystal nucleation are other than of purely local origin and may be widely and fairly uniformly distributed at any given time, at least in the region and under the synoptic conditions surveyed, is strongly hinted. This would appear to have interesting implications in the cloud physics field meriting further investigation.

ACKNOWLEDGMENTS

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ESTIMATION OF VERTICAL AIR MOTIONS IN DESERT TERRAIN FROM TETROON FLIGHTS

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ABSTRACT

Low-level, constant volume balloon (tetroon) flights made from Yucca Flat in the Nevada Proving Grounds of the Atomic Energy Commission are utilized to yield an estimate of the nature and magnitude of vertical air motions in desert areas. It is found that during the day the tetroons oscillate as much as 10,000 feet in the vertical with vertical velocities often exceeding 5 kt., whereas during the night the vertical oscillations are on the order of 100 feet and vertical velocities seldom exceed 0.5 kt. There are indications that during the day, at this particular site, helical circulation patterns exist with axes parallel to the north-south oriented valley floor and with alternating circulation sense across the valley, while during the night the small vertical oscillations are more nearly tied to the local topography. Pure mountain influences on the tetroon trajectories could not be clearly delineated owing to the tremendous vertical oscillations associated with solar heating.

1. INTRODUCTION

The constant volume balloon (tetroon) flights previously reported on by the writers were launched from coastal radar sites at Cape Hatteras [1] and Wallops Island [2], and most of the tetroon trajectories lay over water. As the sea surface presents a fairly homogeneous surface with respect to radiative and frictional influences, it is not surprising that most of these tetroon flights (at least those that were reliably positioned) appeared to remain very nearly at constant level, the exception being two flights which were released within, or close to, a cold frontal zone [2]. Because one of the chief uncertainties with respect to these superpressured tetroons is the degree to which they respond to vertical air motions, it was thought desirable to make some tetroon flights in desert regions where the vertical air motions would be at a maximum. Consequently, during September 1960, 15 tetroon flights were made from Yucca Flat in the Nevada Proving Grounds of the Atomic Energy Commission. The tetroons were tracked and positioned by means of the newly acquired and modified M-33 radar of the Weather Bureau's Las Vegas Research Station. This paper presents some results obtained from this series of flights, with emphasis on the nature and magnitude of the vertical air motions indicated by the tetroons.

2. PREVIOUS WORK WITH NEUTRAL BALLOONS

Several meteorological groups have used neutral or no-lift pibal balloons to estimate vertical air motions near the earth's surface. Probably the most extensive use of this technique was at Oak Ridge, Tenn. between January 1949 and February 1950, as reported by Gifford [5]. Gifford also cites German work along this line, in particular the work of Lange [8] in connection with gliding activities.

Superpressured, constant volume, Mylar balloons (tetroons) offer some advantages with respect to no-lift pibal balloons, particularly for the determination of vertical air motions. These are:

1. The tetroon, being for all practical purposes non-extensible, will not undergo a change in buoyancy force due to variation in balloon volume associated with heating effects, as will the pibal balloon. In particular, tetroons superpressured to 50–100 mb. have the capability of going through sunrise and sunset without change in flight altitude, although this capability has not yet been utilized.

2. The tetroon can, within certain limits, be set to float at a given altitude, whereas the no-lift pibals must, by their nature, be set to float close to the earth's surface.

3. The radar-reflective tetroon can be tracked to greater distances than can no-lift pibals by double theodolite methods, and furthermore tetroon tracking can be accomplished in clouds, at night, etc.

These advantages make it worthwhile again to carry out experiments whose aim is the delineation of 3-dimensional air trajectories. In the following, comparison is often made between the no-lift pibal data of Gifford and the tetroon data obtained at Yucca Flat.

3. FLIGHT PROCEDURES AND DATA OBTAINED

Table 1 shows the time of tetroon release, the flight equipment utilized, the flight level, duration of flight,

*Research undertaken as portion of programs sponsored by Reactor Development Division, Atomic Energy Commission, and Air Pollution Division, Public Health Service.

TABLE 1.—*Tetroon flights from Yucca Flat*

Flight	Date	Launch site	Launched (PST)	Average flight altitude (feet)	Duration at flight altitude (minutes)	Distance tracked at altitude (n. miles)	Equipment	Termination due to—
1	9-19-60	Radar	1213	6200	70	10.3	42″ T, CR	Radar lost contact.
2	9-19-60	Radar	1346	4100	48	6.7	42″ T, 2 CR	Grounded.
3	9-19-60	Radar	1506	3100	58	7.9	42″ T, 2 CR	Radar lost contact.
4	9-19-60	Radar	1749		0	0.0	42″ T, 2 CR, L	Radar lost contact.
5	9-19-60	Radar	1855	1000	15	1.9	42″ T, M, L	Radar lost contact.
6	9-19-60	Radar	2008	160	56	6.1	60″ T, 2 CR, L	Radar lost contact.
7	9-20-60	Radar	0635	1200	101	2.8	60″ T, 2 CR, M	Grounded.
8	9-20-60	Radar	0638		0	0.0	60″ T, CR	Burst.
9	9-20-60	Yucca Wx. Sta	1204	3500	81	15.3	60″ T, 2 CR	Radar lost contact.
10	9-20-60	Yucca Wx. Sta	1456	4200	50	13.2	60″ T, 2 CR	Behind hill.
11	9-20-60	Yucca Wx. Sta	1813		0	0.0	60″ T, 2 CR, M, L	No radar contact.
12	9-20-60	Radar	1925		0	0.0	60″ T, 2 CR, M, L	Caught in power line.
13*	9-20-60	Radar	2336	150	44	2.8	60″ T, CR, M, L	Radar lost contact.
14**	9-21-60	Radar	0702	6300	52	25.3	60″ T, CR, M	Behind hill.
15	9-21-60	Yucca Wx. Sta	0851	2800	64	18.9	60″ T, M	Behind hill.

*Immediately after release, momentarily caught in power line and grounded.
**Towed aloft by radiosonde balloon.

Equipment: T=tetroon, CR=corner reflector, M=radar reflective mesh, L=pibal light.

and other information of possible interest. Flight termination was due to grounding of the tetroon, disappearance of the tetroon behind the mountain ridges surrounding Yucca Flat, and (most often) loss of radar contact with the tetroon as it approached a mountainside due to the appearance of terrain echoes in the radar gate. It is seen from table 1 that reasonably long-range trajectories could be obtained only for flights at relatively high level or for flights released upwind from the radar site.

The positioning accuracy of the M–33 radar is not known with certainty. It has been estimated [3] that the average error in azimuth and elevation angle is about 2 mils (0.11 degrees), leading to height and lateral displacement errors of about 100 feet at ranges near 50,000 feet. The very accurate FPS–16 radar utilized at Wallops Island gave errors of less than 10 feet at such ranges. However, the loss of accuracy in the M–33 is partially offset by its mobility, simplicity of operation, and by the fact that a much smaller crew (2 men) can handle it.

As a consequence of the above positioning errors, at Yucca Flat the tetroon velocity was determined as an average over 1-minute intervals rather than the 30-second intervals utilized on the Wallops Island flights. The horizontal velocity data were derived from dial readings giving tetroon slant range in yards and azimuth angle in mils. However, the digital elevation angle data could not be obtained conveniently owing to the position of the dial and therefore the tetroon height was scaled directly from the plotboard. From the change in tetroon slant range, azimuth angle, and height with time, values of the longitudinal (V_s), transverse (V_n), and vertical (w) velocity components were obtained.

4. TETROON TRAJECTORIES

Figure 1 shows the horizontal trajectories of the 12 successful tetroon flights. The tetroons were released from the radar site and from Yucca Weather Station about 7 miles to the south. The trajectories are based upon tetroon positions every minute but for simplicity in the figure the positions are indicated only at 5-minute intervals. For the sake of clarity, the surface topography has also been traced only at 1,000-foot intervals.

The few tetroon trajectories available suggest the existence of preferred corridors of escape for air flowing northward up Yucca Flat during the midday hours, with one corridor extending northward from Whiterock Spring (as illustrated by the trajectories of flights 1 and 9) and the other corridor extending northward from Oak Spring (as illustrated by the trajectories of flights 14 and 15). A priori, one would not expect that the air flow at such heights (3,000–6,000 feet above the earth's surface) would be influenced by terrain during the hours of daytime instability, and indeed smoke experiments have shown no evidence for such a channeling effect. The evidence for such an effect from the few tetroon data is sufficiently strong, however, to warrant a test series of serial tetroon releases in order to confirm whether or not tetroons released from the given area will ever traverse the highlands between Whiterock Spring and Oak Spring. Note that flight 2 grounded on a spur in this region, suggesting both an unwillingness for air parcels to ascend over these highlands and an uncertainty with regard to which of the above suggested corridors to take.

Possibly associated with the existence of preferred corridors of escape is an intriguing tendency for the azimuth of the end point of the tetroon trajectories to shift regularly in a clockwise sense during the afternoon hours. This tendency is shown in figure 2 by the dots. A regression line, fitted to the afternoon azimuths, indicates an azimuth turning of 9 degrees per hour, precisely the pendulum-day period at this latitude. It is not certain whether this result is coincidental or not. During times of sea breeze, low-level winds obtained from anemometers often turn

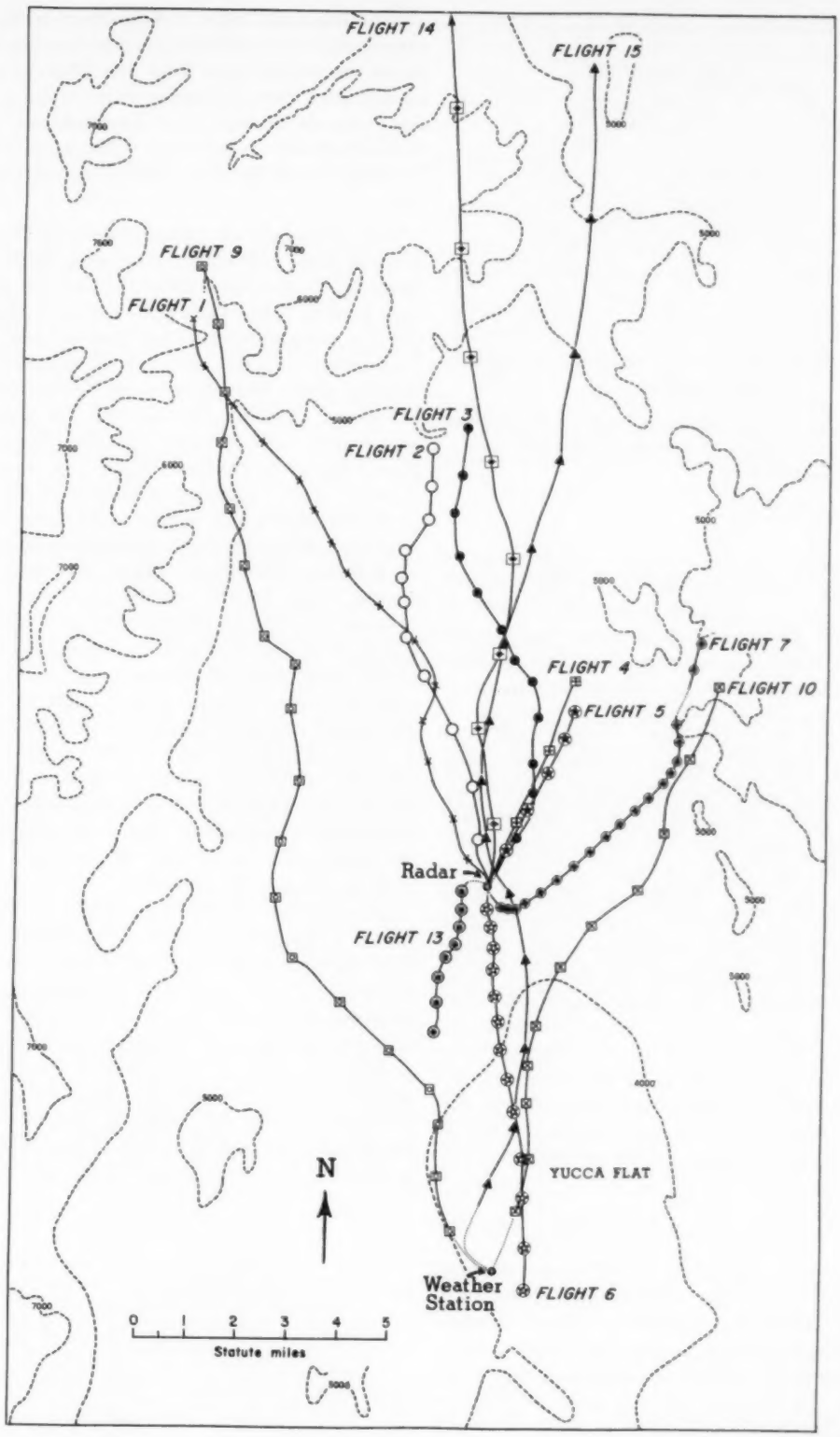

FIGURE 1.—Trajectories of the 12 successful tetroon flights at Yucca Flat, Nevada Proving Grounds. Tetroon positions indicated at 5-min. intervals, ground height (dashed lines) at 1000-ft. intervals. Dotted segments of trajectories estimated from visual sightings.

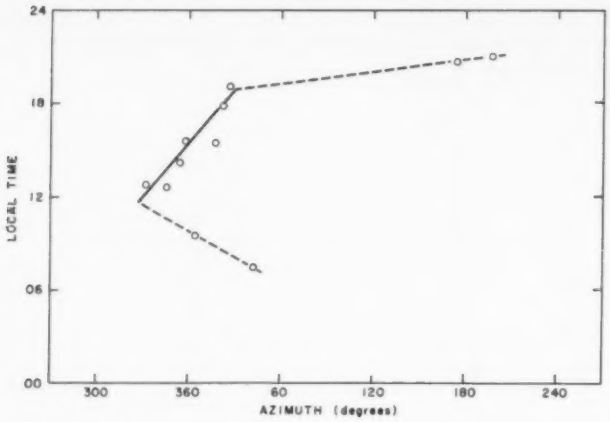

FIGURE 2.—Azimuths of end points of tetroon trajectories (dots) as function of mid-time of flight. A regression line (solid line) is fitted to the afternoon azimuths.

with approximately a pendulum-day period [4] and also the Eulerian-type winds obtained from various sites in Yucca and Jackass Flats indicate a somewhat similar change with time [12]. The tetroon data suggest that these wind-direction changes with time extend to quite high elevations and may not be purely local in nature.

Two of the tetroon flights (6 and 13) went southward down Yucca Flat, embedded in the nighttime drainage flow. Flights 4 and 5 were released early in the evening in an attempt to catch the transition from daytime upslope to nighttime drainage flow, but unfortunately both flights were lost by the radar as they approached the mountainside. In any event the shift might never have been detected from these flights because of the probability that the height of the tetroons above the earth's surface exceeded the depth of the drainage flow during such an early stage of development. In a sense flight 7 detected the transition from drainage to upslope flow with the flight starting out to the southeast and then curving counterclockwise and passing out of the Flat to the northeast. In the following the flights are grouped and discussed according to whether they took place near midday, during early morning or evening, or during the transition period.

5. TETROON HEIGHT FLUCTUATIONS NEAR MIDDAY

Figure 3 shows tetroon height as a function of range for the five flights (1, 2, 3, 9, 10) released during the early afternoon. The essentially north-south height profiles have been positioned relative to the radar site in order that any tendency for similarity among the height traces might be noted. In this case there is only the weakest sort of evidence for ascending motion upstream from the radar, descending motion immediately downstream from the radar, and ascending motion about 30,000 ft. downstream from the radar. Note that in figure 3, and in subsequent figures of this type, the horizontal and vertical scales are identical so that the trajectory slope in the longitudinal-vertical plane is obtained immediately. This slope exceeds 30 degrees for long distances along many of these afternoon trajectories. This is the order of streamline slope found by glider pilots in mountain-wave regimes [13].

The magnitude of 1-minute-average vertical velocities derived from these five afternoon flights is shown in figure 4. Nearly one-fifth of the time the absolute magnitude exceeds 5 kt., with some evidence that in the mean the ascending motions are of greater magnitude than the descending motions. On several occasions the vertical velocity of the tetroon exceeded its horizontal speed.

Table 2 gives an estimate of the average trajectory wavelength and period (in the longitudinal-vertical plane) for each afternoon flight. It is emphasized that these represent Lagrangian scales and do not necessarily yield the length and period appropriate to a streamline pattern. While the wavelengths and periods are difficult to delineate and some subjectivity is undoubtedly involved, basically the wavelengths are on the order of 5–10 mi. and the periods of vertical oscillation are on the order of 30–45 min. By comparison, the Oak Ridge no-lift pibal data of Gifford suggested wavelengths and periods on the order of 5,000 ft. and 15 min. under conditions of strong instability and light wind speed, and wavelengths and periods on the order of 15,000 ft. and 25 min. under conditions of moderate instability and strong wind speed. Thus the period of oscillation in the longitudinal-vertical plane is about twice as great at Yucca Flat as at Oak Ridge while the wavelength is about four times as great.

There exists a "natural" period of air parcel oscillation in the vertical [7, p. 132], which period is infinite for a dry adiabatic lapse rate and is about 10 minutes for the lapse rate (0.7° C./100 meters) usually prevailing in the atmosphere. Both the Wallops Island tetroon flights and the Brookhaven no-lift pibal flights of Gifford [6] indicate a period of oscillation in the vertical somewhat smaller than 10 minutes for the given stability, in rough agreement with the "natural" period. The 40-minute periodicity derived fron the Yucca Flat flights would correspond to the "natural" period only if the lapse

TABLE 2.—*Lagrangian wavelength and period of vertical oscillation for early afternoon tetroon flights from Yucca Flat*

Flight	Wavelength (feet)	Period (minutes)
1	42,000	4
2	26,000	2
3	35,000	4
9	43,000	2
10	51,000	4
Average	39,000	3

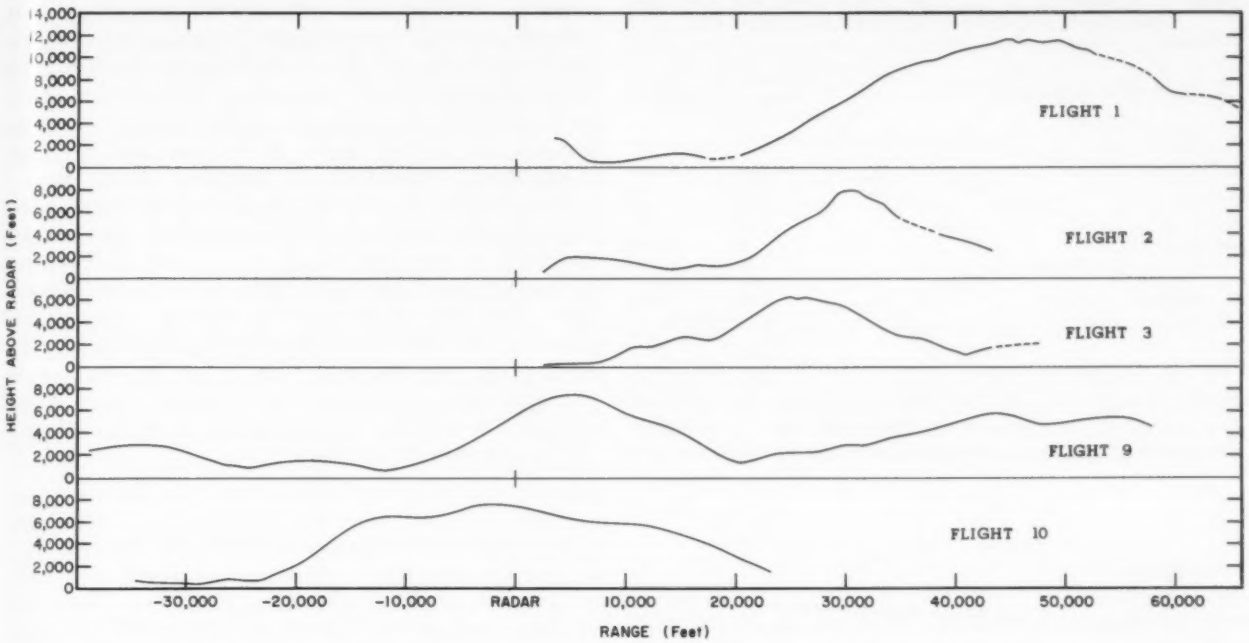

FIGURE 3.—Tetroon height versus distance along trajectory for early-afternoon flights (1, 2, 3, 9, 10) at Yucca Flat. Dashed lines represent interpolated heights.

rate at Yucca Flat during the time of the flights was within 0.02° C./100 meters of the dry adiabatic lapse rate. Both the Las Vegas and Jackass Flat soundings do indeed show that the lapse rate is very close to the dry adiabatic at the time of these flights, with a super-adiabatic lapse rate close to the ground followed by an approximately dry adiabatic lapse rate up to at least 10,000 feet. Thus there is a suspicion that the height fluctuations experienced by tetroons and no-lift pibals may be attuned to a period specified by the existing lapse rate.

With regard to the fidelity with which tetroons follow the vertical air motion, it is of interest to compare the height which air parcels might be expected to attain during the heat of the afternoon (mixing depth) with the height attained by the tetroons. Figure 5 shows early morning (0300 PST) radiosonde soundings for Jackass Flat, some 20 miles to the southwest of Yucca Flat. The dashed lines in this figure represent dry adiabats drawn through surface temperature readings at Yucca Flat during the time of flights 1, 2, and 3 on September 19, flights 9 and 10 on September 20, and flight 15 on September 21.

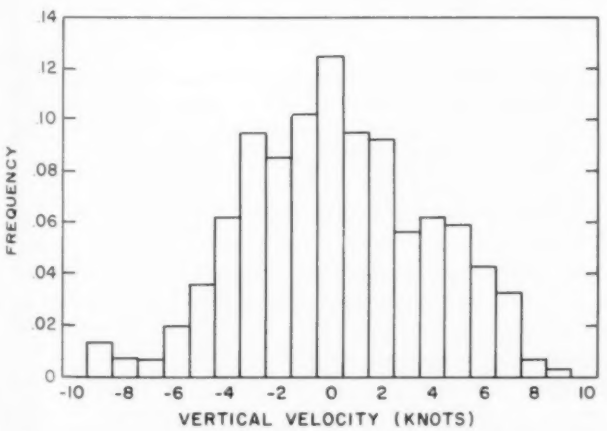

FIGURE 4.—Frequency distribution of 1-minute-average vertical velocities derived from five early-afternoon tetroon flights.

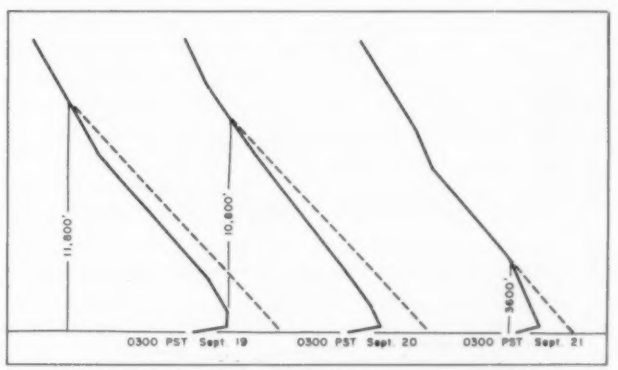

FIGURE 5.—Early-morning radiosonde soundings at Jackass Flat, Nevada Proving Grounds. Dashed lines represent dry adiabats through surface temperature readings at Yucca Flat during times of tetroon flight.

TABLE 3.—*Comparison of maximum tetroon height and air parcel mixing depth for daytime tetroon flights from Yucca Flat*

Flight	Maximum tetroon height (feet)	Mixing depth (feet)
1	11,700	11,800
2	7,900	11,800
3	6,300	11,800
9	7,600	10,800
10	7,700	10,800
15	5,800	3,600
Average	7,800	10,100

The flat temperature maximum at this locality enables a single temperature to represent conditions during more than one flight. Presumably, one would anticipate rather free vertical mixing during the afternoon up to the height where the dry adiabats intersect the sounding curves. Actually, since a superadiabatic lapse rate prevails near the earth's surface in this region during the daytime hours, the mixing depth would be somewhat less than that indicated by the given intersection. Table 3 gives a comparison between the mixing depth so obtained and the maximum height attained by the tetroons. While there is good agreement on some of the flights and poorer agreement on other flights, there is a suggestion that basically the tetroons were oscillating in the vertical through a layer of air which one would expect to be in a mixed condition. This represents evidence that the tetroons were following the vertical air motions to a considerable degree. Apparently, the restoring force acting to displace the tetroons back to their equilibrium density surface is small compared to the drag force acting on the tetroons through the agency of large vertical motions.

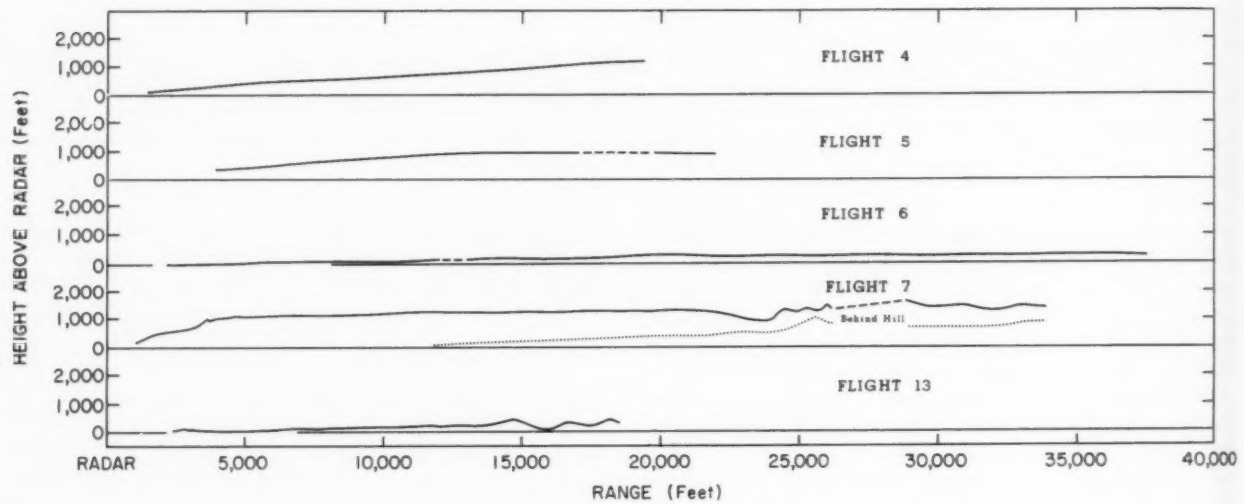

FIGURE 6.—Tetroon height versus distance along trajectory for early morning and evening flights (4, 5, 6, 7, 13) at Yucca Flat. Dashed lines represent interpolated heights. Dotted line indicates surface topography along flight 7.

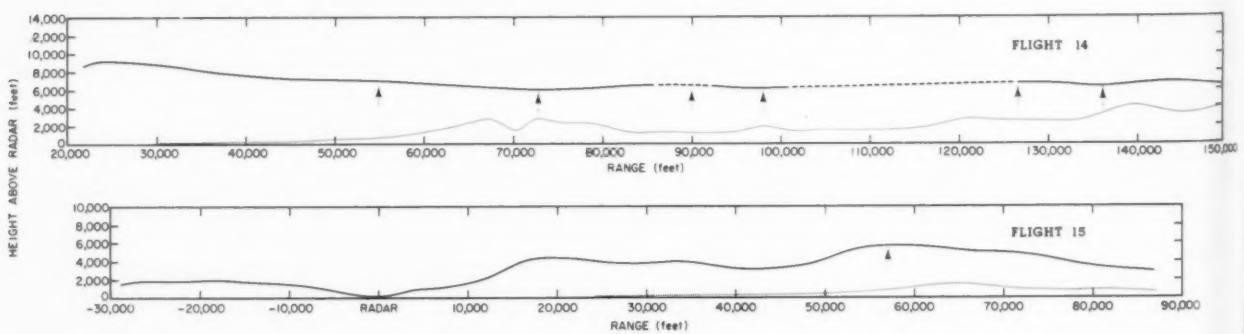

FIGURE 7.—Tetroon height versus distance along trajectory for morning flights (14 and 15) at Yucca Flat. Dashed lines represent interpolated heights, dotted lines indicate surface topography along flights, and solid and dashed arrows indicate positions of maximum and minimum tetroon height.

6. TETROON HEIGHT FLUCTUATIONS AT NIGHT

Figure 6 shows tetroon height as a function of range for the five flights (4, 5, 6, 7, 13) released during the evening and early morning hours. Presumably, these flights are reasonably representative of flight conditions during nighttime. The difference in magnitude of tetroon oscillations in the vertical at night and near midday is striking indeed, with vertical oscillations in the former case on the order of 100 ft. and in the latter case on the order of 1,000–10,000 ft. Furthermore, in contrast to the results presented in figure 4, 84 percent of the 1-minute-average vertical velocities derived from these five flights were within the range −0.5 to 0.5 kt.

The two flights released latest in the evening (flights 6 and 13) flew no higher than 300 and 600 ft. above the ground, respectively, apparently within an inversion surface. It is assumed, therefore, that the vertical oscillations experienced by these flights to some extent mirror the undulations in the inversion surface. Although flight 6 closely followed the contour of minimum height in the valley floor whereas flight 13 followed the contour of 4,080 ft. somewhat to the west, along both flights, in general, the tetroon height slowly and regularly increased with time suggesting either that the inversion surface rises as one moves southward down the Flat or that at this time in the evening there is an increase in inversion height with time. The possibility that the tetroons did not reach their equilibrium altitude is made unlikely by previous experience concerning the length of time it takes tetroons to attain that altitude. The use of tetroons as an inversion-surface tracer (in the Los Angeles Basin, for example) is immediately suggested.

Other than the slow increase in tetroon height with time noted along flights 6 and 13, little in the way of regular height fluctuations was noted on these nighttime flights. The rather large, but intermittent height fluctuations along flight 7 will be considered in relation to mountain effects in the following section.

7. INFLUENCE OF TOPOGRAPHY UPON TETROON HEIGHT

One of the features it was hoped could fairly easily be investigated by means of tetroon flights in the Yucca Flat region was the air flow over mountainous terrain. However, since many of the tetroon flights were confined to Yucca Flat itself and, moreover, since most of the flights were made during the daylight hours when the vertical tetroon oscillations associated with solar heating far outweighed any vertical oscillations associated with topography, the results were disappointing. The only flights suitable for consideration here were those released early enough in the morning to avoid the bulk of the thermal influences and yet which crossed mountain ridges of appreciable size (flights 7, 14, and 15).

The topography along flight 7 has been plotted in figure 6. This flight traversed a mountain pass and

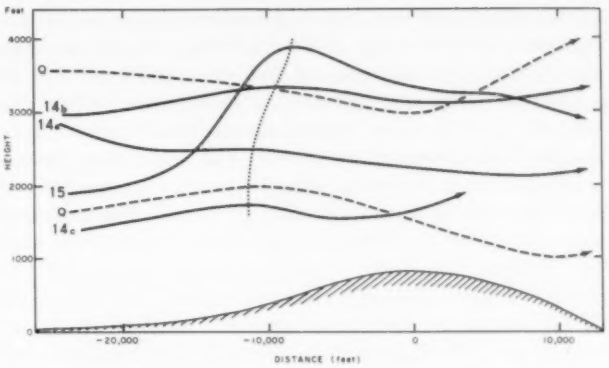

FIGURE 8.—Portions of trajectories of flights 14 and 15 (solid lines) in the longitudinal plane and their relation to a schematic mountain ridge. The dashed lines represent streamlines deduced theoretically by Queney for medium-sized mountains. Dotted line is locus of maximum tetroon heights.

subsequently disappeared behind a hill for over 10 minutes before again being picked up by the radar. The interesting thing is that while this flight was stabilized at a level sufficiently high to avoid an upcoming mountain ridge, upon passing a small hill of no more than 100-foot height, the tetroon descended 400 feet to a level below the ridge. It is suggested that this tetroon descent was induced by descending air motion associated with a hillside slope not yet illuminated directly by the early morning sun. Subsequently the tetroon ascended quite rapidly (400 ft. in 2 min. or at a speed of 2 kt.) to a height sufficient to clear the upcoming ridge. This sudden ascent took place about 2,000 ft. upwind of the ridge itself and as it could hardly have been thermally induced, must have been a purely mechanical consequence of the presence of the mountain ridge.

Figure 7 shows the topography and tetroon height traces along flights 14 and 15. The arrows in this figure indicate places of maximum (solid arrows) and minimum (dashed arrows) tetroon height. In the case of flight 14, which was towed aloft by a radiosonde balloon and flew at an altitude amenable to rather lengthy tracking, the tetroon traversed several mountain ridges of varying size. However, the tow release on flight 14 did not function at the proper altitude with the result that the tetroon, upon release, slowly sank to its design altitude, making the delineation of mountain influences over the initial ridge somewhat difficult. On flight 15 there was a pronounced tetroon ascent a little upstream from the main mountain ridge. On the one hand it would be easy to associate this ascent with air flow over the ridge. On the other hand, since the tetroon had previously undergone a similar rise while over Yucca Flat itself, such an association may be erroneous.

In figure 8 are plotted the height traces (solid lines) along flights 14 and 15 as a function of position with respect to the nearest mountain ridge. The dotted line

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shows that in all cases the maximum tetroon height was reached upstream from the ridge with the distance upstream being on the order of two times the height of the mountain. For comparison we have scaled down and plotted, in the same figure, streamlines (dashed lines) deduced theoretically by Queney [10] for a mountain of medium size. The tetroon height traces agree better with the low-level Queney streamline than with the high-level one. However, it will be apparent to the reader that while the tetroons may have a great potential for the study of air flow over mountains, these particular flights were not ideally suited for such investigations. Consequently this comparison of observed and theoretical streamlines and trajectories will not be carried further.

8. TETROON CIRCULATIONS IN THE TRANSVERSE PLANE

In order to illustrate the nature of tetroon circulations in the transverse plane, a straight line was drawn between initial and final tetroon position at flight altitude and deviations in height and lateral distance from this line were computed at minute intervals. Figure 9 shows these transverse circulations (looking downstream, or northward, up the Flat) for the five afternoon flights. Once again the tetroon positions are indicated at 5-minute, instead of 1-minute, intervals for clarity. It is seen that basically the transverse tetroon circulations have the same vertical and lateral dimensions with an average eddy diameter in the transverse plane of about 5,000 ft. At Oak Ridge, Gifford found eddies of 700-ft. diameter in this plane, nearly an order of magnitude smaller than that found at Yucca Flat.

Flights 2, 9, and 10 possess a clockwise circulation in the transverse plane whereas flights 1 and 3 possess a counterclockwise circulation in this plane. Figure 9 shows the manner in which the flights were ordered across the Flat, from the flight that went farthest to the west (flight 9) to the flight that went farthest to the east (flight 10). It is seen that when the flights are ordered in this way the sense of the transverse circulation alternates so that there is agreement among the flights as to the position of upward and downward motion. Thus, although it appears unlikely that systematic circulation patterns could be maintained for a period of hours in such a region of intense circulation, the possibility at least exists that the air circulation in Yucca Flat consists of a series of helices, perhaps fixed with respect to terrain features, with axes running approximately north-south. Figure 10 shows the vertical motion pattern which results when an attempt is made to draw to the vertical velocity data, obtained from the five afternoon tetroon flights, with such helical circulation in mind. The axes of the helices, or longitudinal rolls, are spaced 15,000–25,000 ft. apart and are positioned in such a way that the ascent portion of the helical circulation occurs over the western extremity of the Flat but apparently not over the eastern extremity.

It should be emphasized at this point that the vertical motion pattern derived from the five afternoon flights, and presented in figure 10, is not unique. Along the line of the discussion in Section 4, the vertical motion pattern could also be drawn in the form of transverse rolls oriented across Yucca Flat, as in figure 11. The pattern in figure 11 appears as reasonable as that presented in figure 10; in fact, most meteorologists, if simply handed the data, would probably analyze them in the form presented in figure 11. The question now arises, which of the circulation patterns (assuming persistence for either pattern) presented in figures 10 and 11 is the more basically correct,

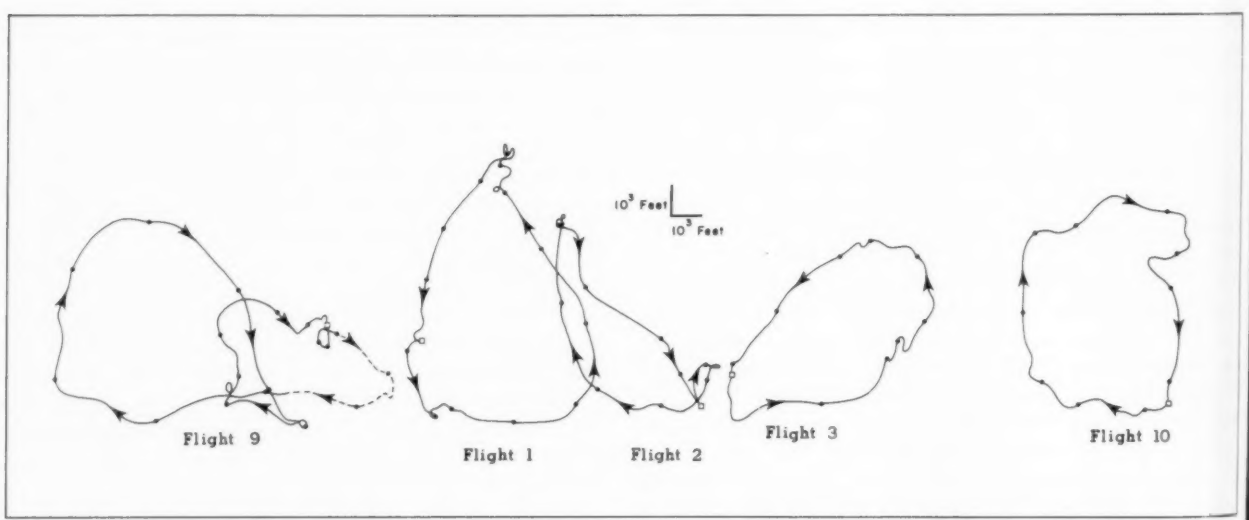

FIGURE 9.—Tetroon circulations in transverse plane (looking downstream or northward up Yucca Flat) for early-afternoon flights. Tetroon positions at 5-min. intervals. Circulation patterns ordered and spaced across the Flat in agreement with trajectory location.

or can both occur depending upon wind shear and stability conditions? For independent verification we have only flight 15 which was released during the morning hours just as the daytime vertical motion systems were becoming organized. Figure 12 shows a portion of the height trace of flight 15 (dashed line) in comparison with the height trace of a hypothetical flight up the middle of the Flat, as deduced from the vertical motion pattern of figure 11. There is general agreement in the two traces with indications of height maxima 35,000 and 65,000 ft. north of Yucca Weather Station and height minima 50,000 and 75,000 ft. north thereof. Added support for consideration of the oscillations as transverse rolls comes from the approximate agreement in ratio between mixing depth and (Lagrangian) wavelength obtained from the daytime tetroon flights (1/3.4) and the ratio of 1/2.7 specified

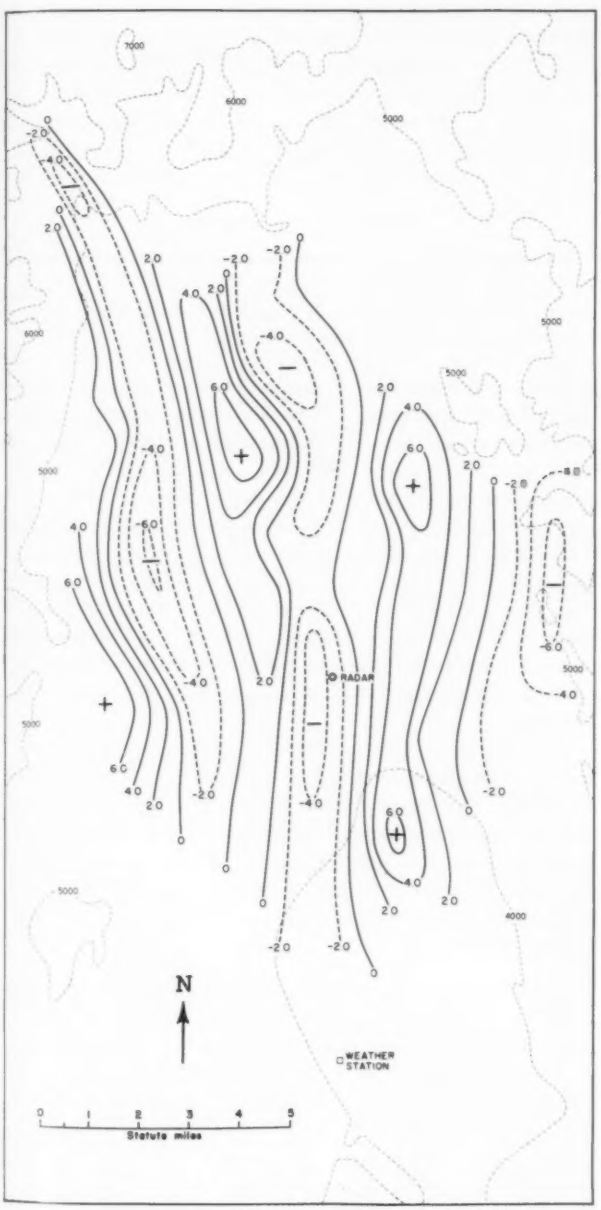

FIGURE 10.—Isopleths of 5-minute-average vertical motion (knots) in Yucca Flat derived from the five early-afternoon tetroon flights assuming helical (longitudinal-roll) circulation patterns.

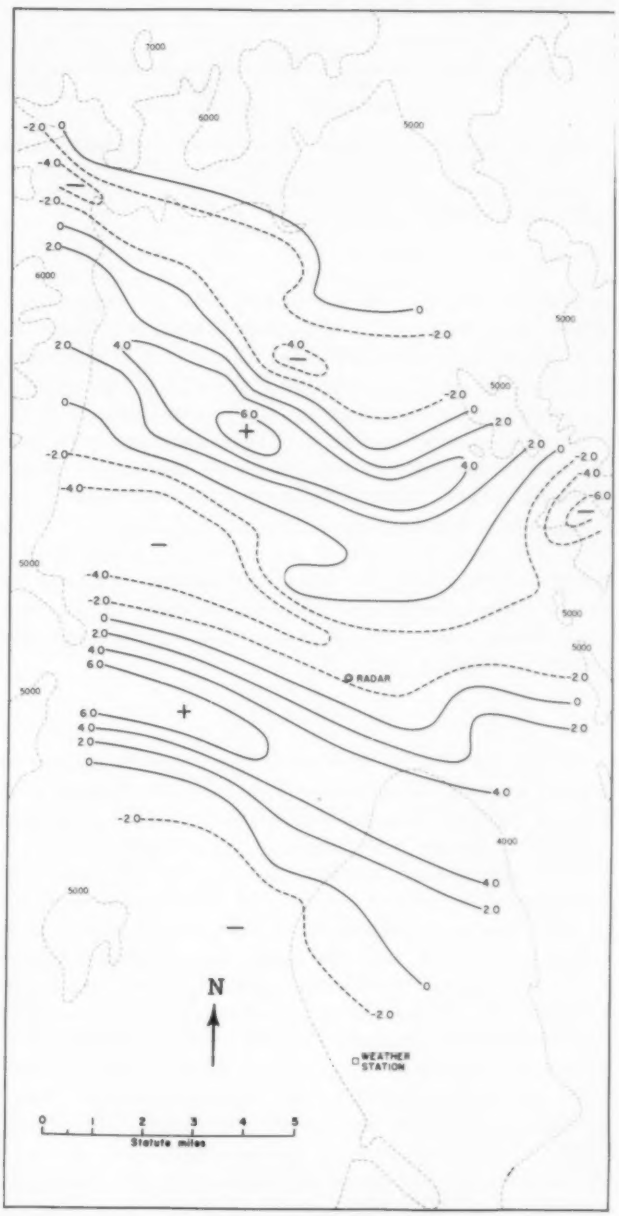

FIGURE 11.—Isopleths of 5-minute-average vertical motion (knots) in Yucca Flat derived from the five early-afternoon tetroon flights assuming transverse-roll circulation patterns.

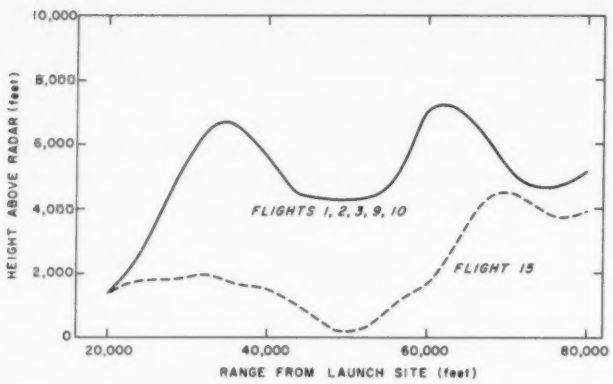

FIGURE 12.—Height trace (solid line) of hypothetical midday flight north up Yucca Flat derived from isopleth pattern in figure 11 (based on flights 1, 2, 3, 9, 10) and portion of height trace of morning flight 15 (dashed line).

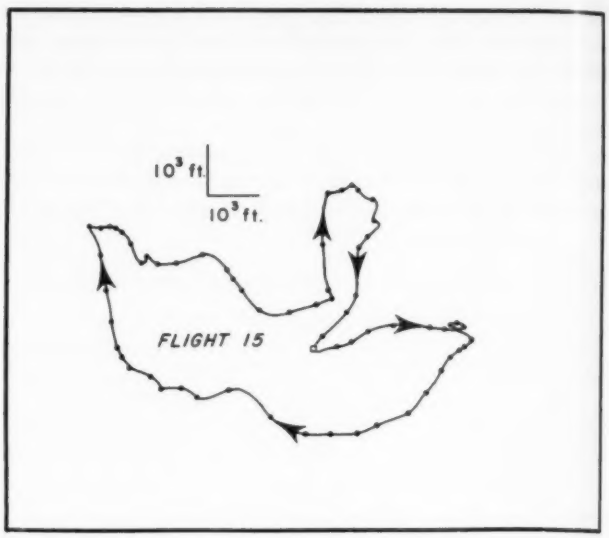

FIGURE 13.—Tetroon circulation in transverse plane (looking downstream or northward up Yucca Flat) for morning flight 15. Tetroon positions at 1-minute intervals.

by Scorer [13, p. 154] as appropriate to such rolls.* When the transverse circulation pattern of flight 15 (fig. 13) is compared with figure 9, however, the agreement is seen to be very poor because flight 15 has the opposite transverse circulation sense to flight 3 and yet the flight trajectories almost coincide. This discrepancy is not necessarily fatal to the postulation of helical circulation patterns because some east-west shift in the axes of the helices might be expected as the sun rises higher. With the data sample available the problem is moot and solution lies either in the simultaneous tracking of two or more tetroons or in the combination of the Lagrangian tetroon data with Eulerian data of the type discussed by Richter [11].

9. STATISTICS

While it is not the purpose of this paper to discuss at length velocity statistics derived from the Yucca Flat tetroon flights, it is useful to consider briefly a few vertical velocity statistics and indicate their relation to other velocity component values. Information of this type is presented in table 4. It is seen that in the mean for all the Yucca Flat flights the root mean square vertical velocity is 2.4 kt. and the turbulence intensity is 0.25, while the ratio of root mean square vertical and longitudinal, and vertical and transverse velocity components is 0.88 and 0.80 respectively. The Wallops Island data, involving overwater trajectories, gave values of 0.07, 0.80, and 0.46, respectively, for these parameters. Thus, in comparison with the overwater flights, the desert flights yield a considerably greater turbulence intensity in the vertical and show a lessening of the transverse velocity variability with respect to the vertical velocity variability, as might be expected.

*Brought to the attention of the writers by Mr. James E. Caskey, USWB.

There is considerable variation in the above values with time of day, however. Thus at Yucca Flat the ratio of root mean square vertical and longitudinal velocities varies from somewhat more than one during midday to about one-half at night, whereas the ratio of root mean square vertical and transverse velocities varies considerably less. This result is in qualitative agreement with the (Eulerian) findings of Panofsky [9] on a much smaller scale; namely, that the variability of the transverse velocity is much more dependent upon stability than is that of the longitudinal velocity so that the ratio of transverse and longitudinal variability is much larger during the day than at night.

Correlation coefficients between wind speed and vertical motion are also presented in table 4. In the mean for all flights the wind speed is stronger with descending motion than with ascending motion so that momentum is being transported downward, as would be anticipated. On some individual flights, however, momentum is being transported upward, particularly during the first day of tetroon flights.

TABLE 4.—*Vertical velocity statistics derived from Yucca Flat tetroon flights. (Height in feet, speed in knots, σ is the root mean square. R is correlation coefficient.)*

Flight	Launched (PST)	$\overline{H}$	$\overline{V}$	σ_w	$\sigma_w/\overline{V}$	σ_w/σ_{V_n}	σ_w/σ_{V_s}	Rv_sw
1	1213	6200	9.2	3.7	0.40	1.23	1.54	0.28
2	1346	4100	8.7	3.6	.41	1.24	1.33	−.02
3	1506	3100	8.6	2.9	.34	1.04	1.21	.14
6	2008	160	6.5	0.3	.05	.38	.16	.00
7	0635	1200	3.7	0.5	.13	.56	.45	−.04
9	1204	3500	12.3	3.6	.29	.74	1.16	.09
10	1456	4200	12.1	3.6	.30	.92	1.20	−.33
13	2036	150	4.2	0.5	.12	.42	.28	−.16
15	0851	2800	17.8	3.1	.17	.69	.58	−.34
Average		2800	9.2	2.4	.25	.80	.88	−.08

10. CONCLUSION

While information on the nature and magnitude of vertical air motions over Yucca Flat has been obtained from these preliminary flights, much still remains to be learned about the 3-dimensional air circulation in this region. In particular:

1. It is not apparent whether the vertical circulation patterns over Yucca Flat are in the form of transverse or longitudinal rolls (helices) or whether both or neither may occur in dependence upon wind shear and stability.
2. The influence of topographic features upon the air trajectories has not been clearly delineated.
3. The transition from upslope to drainage flow, and vice versa, has not been successfully explored.

Future tetroon flights in the Yucca Flat area should provide solutions to some of these problems.

ACKNOWLEDGMENTS

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ACCURACY OF THE AIRBORNE ECONOMICAL RADIOMETER

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ABSTRACT

Further data are presented to indicate the accuracy of the airborne economical radiometer (frequently termed radiometersonde when used in a modified radiosonde system) in the measurement of infrared radiation, in view of its recent widespread use. Three aspects are discussed. The first deals with a nocturnal ground comparison of the economical radiometer with a Suomi ventilated radiometer. The second covers an analysis of random errors in the net radiation obtained with the economical radiometer in the radiometersonde system. And, finally, an experimental in-flight verification of the correctness of the conductivity term in the equations for the economical radiometer is discussed.

1. INSTRUMENT COMPARISON

A comparison of the Suomi ventilated radiometer [1] and the airborne economical radiometer [2, 3] was carried out 1.5 meters above homogeneous terrain during July 1961 at Madison, Wis. Consecutive nocturnal readings of both instruments taken at a sample rate of one each minute, resulted in 203 readings. The net radiation range observed was from 0.0091 to 0.1224 langley per minute. Recently Tanner et al. [4] discussed the accuracy of the economical radiometer in daytime measurements of total radiation.

The statistical results of the frequency distribution of the difference in net radiation observed with the airborne economical radiometer and the Suomi radiometer are presented in figure 1. The class interval for figure 1 is 0.0010 langley per minute. The mean difference between net radiation observed with the airborne radiometer and the ventilated net radiometer is 0.001059 langley per minute with an r.m.s. deviation of 0.001974 langley per minute.

The mean scale factor of the airborne radiometer to the ventilated radiometer is 1.01029 with an r.m.s. deviation of 0.02017. The reproducibility of the airborne radiometer readings during nighttime conditions is apparent from the results.

2. ERROR ANALYSIS

In a consideration of the effects of various possible random and systematic errors in the measurement of the downward- or upward-propagating radiation stream with the radiometersonde in balloon ascents, two sources of error are suggested by the general equation of Suomi and Kuhn [2, 3]. They are random errors in conduction and black body radiation resulting from temperature measurement errors and systematic errors in conduction due to variations in the vertical dimensions of the instrument. We consider, first, errors in the temperature measuring system of the top and bottom sensing surfaces of the radiometer. The expression for net radiation obtained from equation (1) of Suomi, Staley, and Kuhn [3] may be written:

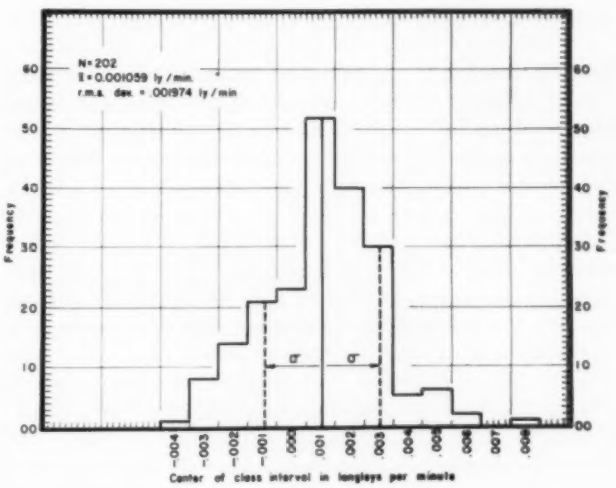

FIGURE 1.—Frequency distribution of the difference in net radiation observed with airborne economical radiometer (radiometersonde) and the Suomi ventilated radiometer.

$$R_N=\sigma[T_b^4-T_t^4]+2\left[a\left\{\frac{T_b+T_t}{2}\right\}+b\right][T_b-T_t]$$
$$-\left[c\left\{\frac{T_a+T_b}{2}\right\}+d\right][T_a-T_b] \quad (1)$$
$$+\left[c\left\{\frac{T_a+T_t}{2}\right\}+d\right][T_a-T_t]+K\lambda\frac{d[T_t-T_b]}{dt}$$

where R_N is net radiation in langley per minute; σ is 0.817×10^{-10} ly. min.$^{-1}$ °K.$^{-4}$; T_t is observed top sensor temperature, (°K.); T_a is observed air sensor temperature, (°K.); T_b is observed bottom sensor temperature, (°K.); t is time in seconds; K is constant (1.45); and λ is constant product of effective specific heat and effective mass/cm.^{2} of the point-thermistor-Mylar sensor surface experimentally found from speed of response to be 7×10^{-3} cal./cm.^{2} deg.; a is 0.000005489 langley/minute °C.; b is 0.001804 langley/minute; c is 0.000010979 langley/minute °C.; and d is 0.003608222 langley/minute.

The last term on the right side of equation (1) is identically zero when the radiometer is tested on the ground.

Differentiating equation (1) we obtain

$$dR_N=[4\sigma T_b^3+(2a+c)T_b+2b+d]dT_b$$
$$+[-4\sigma T_t^3-(2a+c)T_t-2b-d]dT_t. \quad (2)$$

The variance of the net radiation may be expressed as:

$$\text{VAR}\,[R_N]=k_1^2\,\text{VAR}\,[T_b]+k_2^2\,\text{VAR}\,[T_t] \quad (3)$$

where k_1 is equal to the first term in brackets on the right side of equation (2) and k_2 is equal to the second bracketed term. T_b and T_t are independent of one another, but a standard error of 0.2° C. is assumed for each. The 0.2° C. for the r.m.s. deviation was obtained after careful checks of the highest accuracy obtainable in reading the radiometersonde recorder chart and after extended measurements of the normal noise in the recorder system. This random error, of course, does not include the fixed bias error of the radiosonde receiver-recorder system, but the latter effect is of the second order.

Two cases were solved for equation (3): one in which the top and bottom radiometer temperatures were −70.0° C. and −40.0° C., respectively, typical of the high troposphere or low stratosphere, and in the other in which these temperatures were 0.0° C. and 15.0° C., typical of the lower troposphere. Computation gave a standard error of 0.0027 langley per minute in the first case and 0.0041 langley per minute in the second. The former produces an r.m.s. fluctuation of about 1 percent in the upper tropospheric net radiation value. We can also express the variance as the rate of temperature change in a 50-mb. layer of the atmosphere (see equation (1) in Kuhn, Suomi, and Darkow [5]). Since

$$\frac{\partial T}{\partial t}\,(\text{°C./day})=\left[\frac{1440\,g}{c_p\Delta p}\right][R_{N_{upper}}-R_{N_{lower}}], \quad (4)$$

the variance of the left and right sides of this equation becomes

$$\text{VAR}\,[\partial T/\partial t]=\left[\frac{1440\,g}{c_p\Delta p}\right][2]\,[\text{VAR}\,(R_N)] \quad (5)$$

where $\partial T/\partial t$ is the rate of temperature change due to the divergence of the net radiation in the vertical, g is the acceleration of gravity, c_p is the specific heat of air at constant pressure, Δp is the pressure thickness of the layer considered, and R_N is the net radiation.

Solving equation (5) for the two cases cited above yields standard errors in the daily rate of radiational temperature change for 50-mb. atmospheric layers of 0.45°C. and 0.68°C., respectively. For a 100-mb. layer cases I and II give standard errors of 0.23°C. and 0.34°C. per day, respectively. These results, of course, involve no smoothing, which would tend to reduce the standard error. The 50-mb. layer results give a median error of 0.50°C. for all ascent levels, to be compared with an earlier estimate of 0.60°C. [5]. The results described in this section are summarized in table 1.

TABLE 1.—*Standard error of net radiation, and of the daily rate of radiational temperature change for 50-mb. and 100-mb. atmospheric layers.*

	Net radiation	$\partial T/\partial t$ (50-mb. layer)	$\partial T/\partial t$ (100-mb. layer)
Case I	0.0027 ly./min.	0.45° C./day	0.23° C./day
Case II	0.0041 ly./min.	0.68° C./day	0.34° C./day

3. CONDUCTIVITY TERM

In July 1958, a special balloon ascent was made carrying a "disc" type radiometersonde as well as the conventional radiometersonde. Details of this flight over Madison, Wis. were reported in [6]. The importance of the "disc" radiometersonde in this simultaneous ascent becomes apparent from figure 2. Since it is exposed to the same

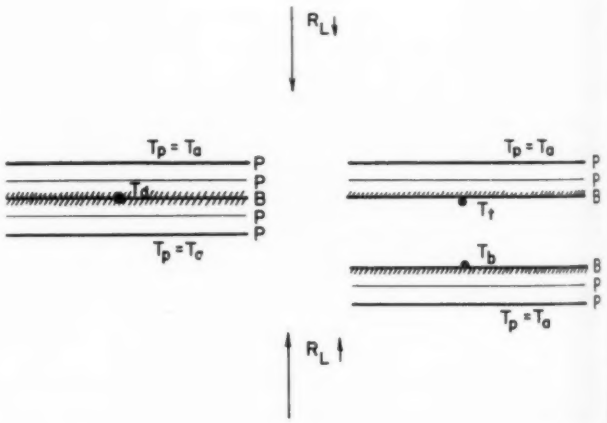

FIGURE 2.—Cross section of the disc airborne economical radiometer (left) and standard airborne economical radiometer (right). Cross hatching indicates blackened aluminum sensing surface; R_L is infrared radiation current; black dots are temperature sensors; subscripted T's refer to polyethylene, air, top, and bottom temperatures; upper case P's to polyethylene ventilation shields.

TABLE 2.—*Comparison of total radiation computed from equation (7) for standard radiometersonde and from equation (6) for "disc" radiometersonde*

Pressure (mb.)	R_{tot} (stand.)	R_{tot} (disc)	R_{tot} (disc) − R_{tot} (stand.)
900	1.130	1.165	−0.035
500	0.830	0.800	0.030
485	0.797	0.765	−0.032
350	0.600	0.566	−0.034
300	0.525	0.490	−0.035
250	0.440	0.433	−0.007
100	0.340	0.338	−0.002
90	0.345	0.340	−0.005
82	0.346	0.345	−0.001
72	0.347	0.351	0.004

streams of upward and downward propagating infrared radiation, it is clear that in the solution of the radiative balance equation for the "disc" radiometersonde there is no internal conduction term. Furthermore, in those instances when the upper and lower polyethylene (air) temperatures are equal to the disc temperature there can be no conduction between the outer polyethylene ventilation shield and the blackened "disc" surface.

If, then, the total radiation is measured both with the "disc" radiometer and the standard radiometersonde, the accuracy of the measurement of the internal conduction, top polyethylene to top sensing surface and bottom polyethylene to bottom sensing surface can be checked.

The total radiation measured by the "disc" radiometersonde is given by,

$$R_{tot}=2\sigma T_d^4-2\left[c\left(\frac{T_a+T_d}{2}\right)+d\right][T_a-T_d]+\left[\frac{K\lambda}{2}\frac{dT_d}{dt}\right] \quad (6)$$

where T_d is the observed "disc" temperature and the constants are defined as in equation (1). The total radiation measured by the standard radiometersonde is given by,

$$R_{tot}=\sigma(T_t^4+T_b^4)-\left[c\left(\frac{T_a+T_t}{2}\right)+d\right][T_a-T_t]$$

$$-\left[c\left(\frac{T_a+T_b}{2}\right)+d\right][T_a-T_b]+[K\lambda d(T_t+T_b)/dt] \quad (7)$$

where all terms are defined as in equation (1). Considering only those levels of the ascent where T_a-T_d in equation (6) is equal to or less than −1.2°C., we have computed R_{tot} from equations (6) and (7) and compare them in table 2.

The data of the last column of table 2, the deviation of the disc from the standard radiometer, display a mean value of −0.0117 langley per minute. The r.m.s. deviation is 0.0206 langley per minute. The mean deviation of the total radiation measured by the two instruments is approximately 2 percent. Since the same absorptivity for the blackened sensing surfaces is used in both instruments and since the same run polyethylene was used in both instruments it is evident that there is no lateral conduction loss. For if there were lateral losses the total radiation measured by the standard radiometersonde would be at best equal to that of the disc for a symmetric temperature profile (i.e., the air temperature is the mean of the observed top and bottom radiometer temperatures). Thus it is believed that the small discrepancy (2 percent) in the observed total radiation values springs in part from the baseline calibration and in part from the fact that T_a-T_d in equation (6) was −1.2° C.

In view of the importance assigned to atmospheric measurements of infrared radiation with the radiometersonde, it is believed that all indications to date suggest its continued use. Studies such as atmospheric flux emissivity, tropopause radiation, satellite radiation comparisons, and others are currently underway.

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TROPOSPHERIC OZONE: AN AIR POLLUTION PROBLEM ARISING IN THE WASHINGTON, D.C. METROPOLITAN AREA

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ABSTRACT

Weather fleck observed on certain varieties of tobacco since 1952 at the U.S. Department of Agriculture Plant Industry Station, Beltsville, Md., may be indicative of an ozone air pollution problem arising in the Washington, D.C. area. A study of ozone concentrations and meteorological conditions existing prior to and at the time of the occurrence of weather fleck indicates that the high ozone concentrations result from the local formation of ozone due to the photochemical reaction of nitrogen dioxide and certain hydrocarbons in the atmosphere of large cities. This reaction is possibly enhanced by the prior advection of an enriched-ozone tropospheric air mass.

1. INTRODUCTION

Ozone has been recognized for some years as one of the more important stratospheric gases. Although its concentration is very low compared to concentrations of other atmospheric gases, its physical properties give it an important role in the heat balance of the stratosphere. Tropospheric ozone on the other hand was usually considered to be unimportant since its concentration (ozone density) was only one-fiftieth of that in the stratosphere. In terms of concentrations expressed in parts per hundred million (pphm) by volume, surface concentrations are only 1/300 of those in the stratosphere. This negligible surface concentration is due to the continuous destruction of ozone near the earth's surface by oxidation with dust and other atmospheric pollutants with which it comes in contact.

The source for most of the tropospheric ozone is the stratosphere. However in the last decade another source of tropospheric ozone has been demonstrated to be of importance in atmospheric pollution problems. Laboratory experiments [1] indicate that nitrogen dioxide and hydrocarbons present in certain concentrations when irradiated by sunlight react to form ozone. The effluent from automobile exhausts, industrial plants, oil and gas heating, and refuse incinerators injects large amounts of hydrocarbons and nitrogen dioxide into the atmosphere. It has been found that under the proper meteorological and topographical conditions ozone concentrations in urban areas may rise to 10 to 20 times the average. The Los Angeles Basin "smog" condition is one of the better documented examples of the problems which may arise in

FIGURE 1.—A typical example of "weather fleck" injury on the upper surface of a tobacco leaf.

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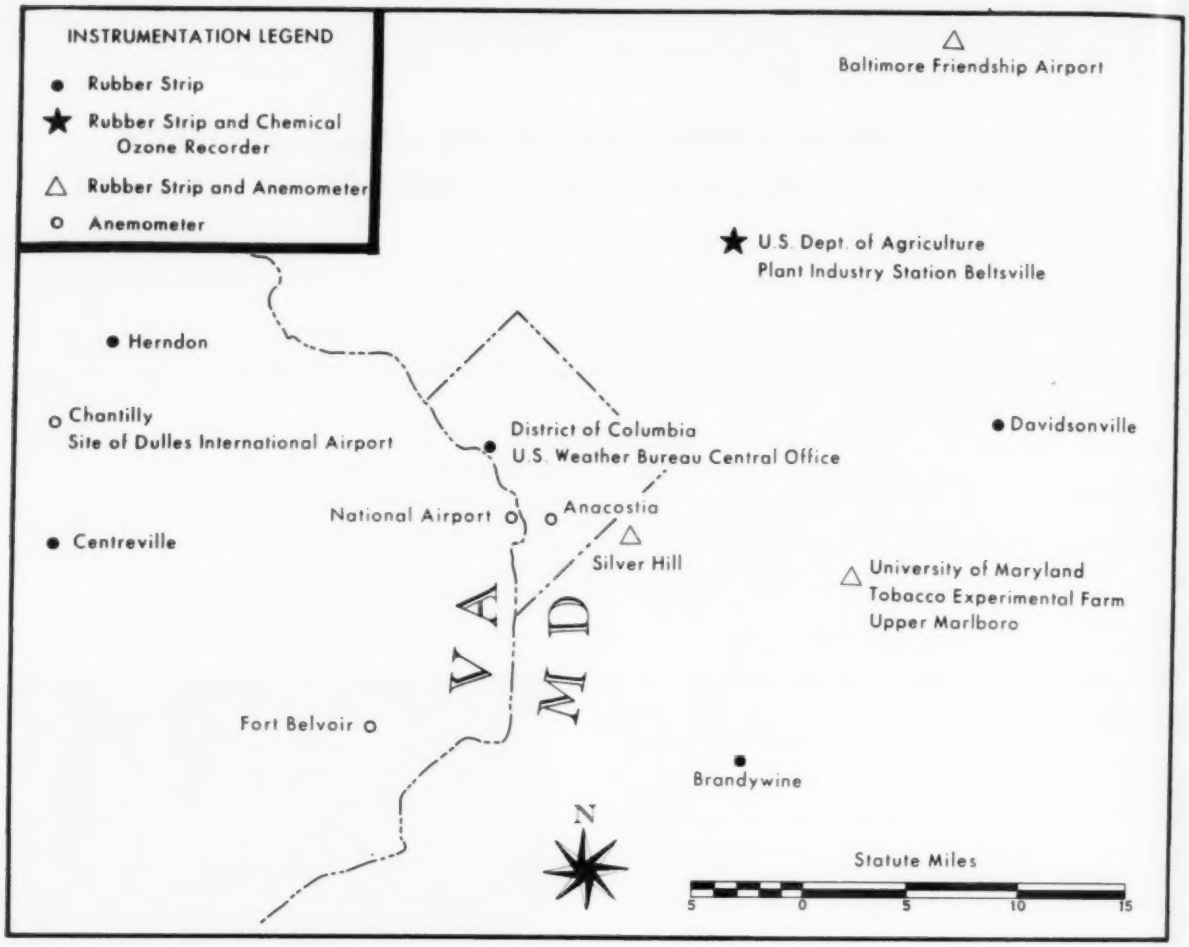

FIGURE 2.—Location of stations employed in the "rubber-strip" network during September and October 1959.

a large city when it is subjected to an atmosphere containing large amounts of ozone and other oxidants. Deterioration of materials, damage to crop and other plants, reduction of visibility, and deleterious physiological effects are greatly increased.

One of the more sensitive indicators of the onset of the ozone-type pollution problem is the appearance of certain types of leaf damage to sensitive plants. For example, Heggestad and Middleton [2] have shown particular varieties of tobacco are subject to a leaf injury known as "weather fleck" or "fleck" (fig. 1). The lesions which occur on the leaf in the fields were reproduced by ozone in chambers with concentrations of about 25 pphm for 6.5 hours. Ozone at concentrations up to 30 pphm for 8 hours resulted in fleck and other types of leaf marking on 14 of 30 plant species tested [3]. Six of the 14 were marked after exposure for 8 hours at less than 10 pphm. Since 1952 fleck has been observed on tobacco plants at the U.S. Department of Agriculture Plant Industry Station, Beltsville, Md., located about 6 miles northeast of Washington, D.C. Some fleck may have occurred prior to 1952, but there are no records of such occurrence. This commencement of fleck damage in this area may indicate that the Washington Metropolitan area is being subjected to an increasing number of events of ozone pollution. However, because of different topographical and meteorological conditions it is unlikely that Washington will ever be subjected to smog conditions as severe as those found in Los Angeles.

The examination of the meteorological conditions existing at the time of high ozone concentration was begun in 1958 as a joint project of the U.S. Weather Bureau and the Department of Agriculture Plant Industry Station. The results of that project have been reported [4]. The project was continued in 1959 and a small network of ozone-measuring stations surrounding Washington was added. The results for the 1959 period are the subject of this paper.

2. RUBBER-STRIP NETWORK

In the 1959 tobacco growing season a small network of

stations was established at which rubber strips were exposed daily. These stations were operated during the months of September and October. The locations of the stations with respect to the district of Columbia are shown in figure 2.

The use of rubber strips as instruments for the detection of ozone, described previously [5, 6], will be discussed here only briefly. When rubber is under tension, ozone causes a particular type of cracking (fig. 3). Laboratory investigations have shown that this cracking is due only to ozone. However, because of the number of parameters which influence the action of ozone on rubber, the determination of atmospheric ozone is more qualitative than quantitative. Parameters which are important are: (1) Nature of formulation and degree of stress of the rubber compound. (2) Concentration of ozone. (3) Time and method of exposure, including shading. (4) Amount of ventilation received by rubber. (5) Temperature and humidity.

Some subjectivity is encountered in determining the degree of cracking as the strips are examined under a low-power microscope. The results depend somewhat on the visual acuity of the observer.

Rubber strips, 40 mm. × 8 mm. × 1 mm., were bent and placed under stress by mounting them in spring clips which at most stations were suspended within inverted plastic-coated paper drinking cups. The bottoms of the cups were cut half open and interiorly baffled to provide both shade and natural ventilation. Exposures at Centreville from October 15 were made inside a standard weather instrument shelter. Two rubber strips were exposed side by side in the same clip at Brandywine and at the Weather Bureau Central Office; only one strip was exposed at other stations. At Beltsville the spring clips were suspended below a horizontal plank and at Upper Marlboro two strips, one below a standard shelter, the other inside the shelter, were exposed. The depth of individual cracks was measured under low-power magnification and totaled for two freshly cut edges of each strip by the procedure employed by Haagen-Smit and Bradley [5]. Where two strips were exposed, the average total was obtained.

The rubber-strip network operated from September 10 through October 25, 1959. All strips from Beltsville, Centreville, and Upper Marlboro were evaluated for total crack depth. Because of cost considerations, strips from the entire network were evaluated for only September 22 to October 7, 1959.

In addition to the rubber strips, the U.S. Department of Agriculture Plant Industry Station operated an automatic chemical ozone meter similar in principle to the one used in 1958 [2, 4]. Because of uncertainties regarding the absolute values of ozone concentration indicated by the recorder, a relative scale of 0 to 100 is employed in this paper to express the daily peak concentration. During the 1959 season, the ozone meter operated satisfactorily from September 21 to October 7, except on October 3 and 6.

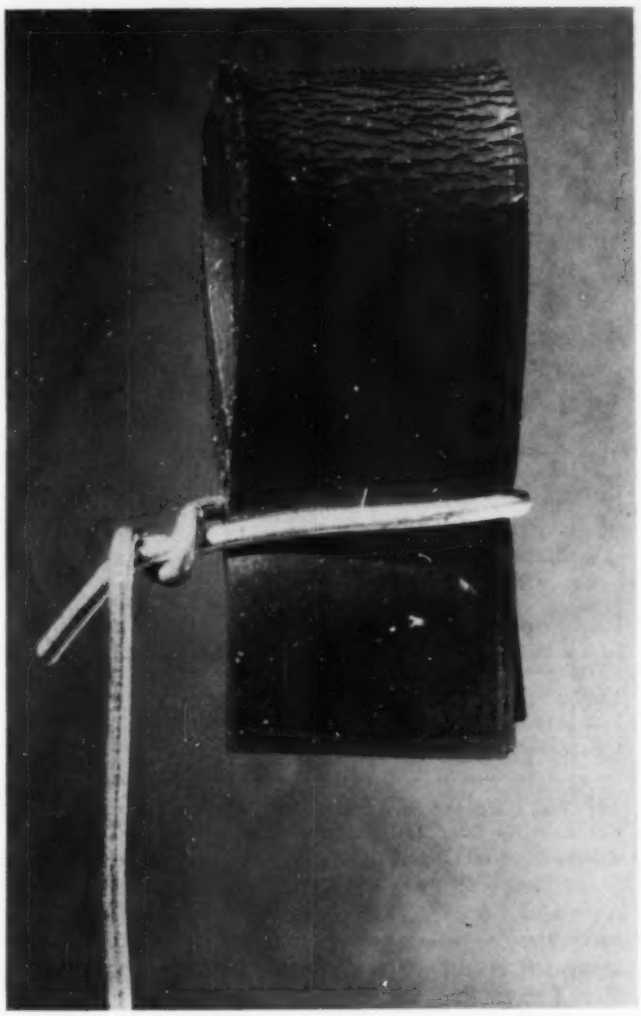

FIGURE 3.—Typical cracking of a rubber strip under tension when exposed to atmospheric ozone.

3. HIGH-OZONE DAYS

In the paper already cited [4] a high-ozone day is defined as one on which an 8-hour average of ozone concentration was 31 or greater on our relative scale of 0 to 100. On this scale the average daily peak value was 29 and the median was 22, whereas on high-ozone days the peaks ranged from 62 to 100. Two days in the 1959 series, September 23 and 24, with relative peak concentrations of 62 and 68 at 1110 and 1215 EST, respectively, qualified as high-ozone days by our definition. On the remaining 15 days, the daily peak values ranged from 14 to 46.

4. CORRELATION OF RUBBER CRACKING WITH AVERAGE OZONE CONCENTRATION

On high-ozone days in 1958, the times of peak values ranged from 0955 to 1505 EST. When the peak occurred

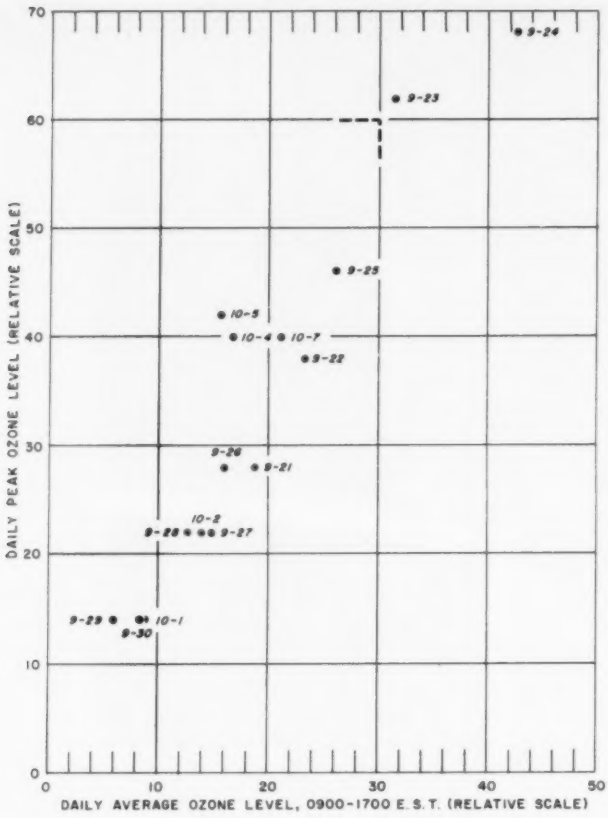

FIGURE 4.—Scattergram of daily peak and average ozone values (0900–1700 EST) on a relative scale at Beltsville, Md.

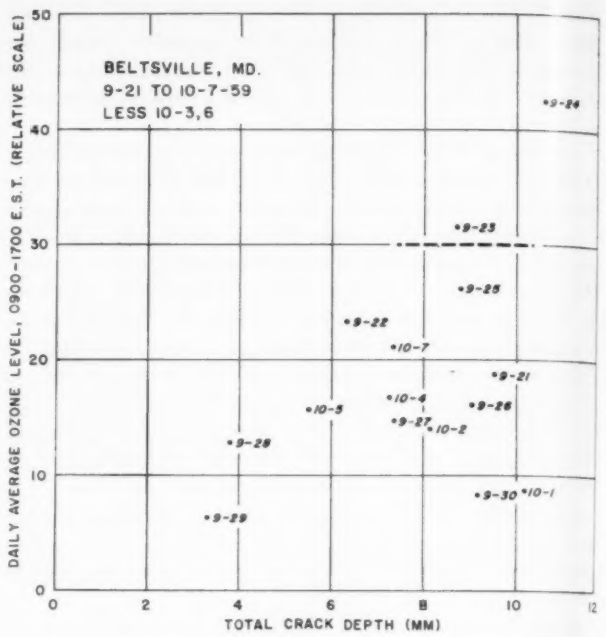

FIGURE 5.—Scattergram of total crack depth (mm.) and daily average ozone values (0900–1700 EST)

early, the rise from near-zero values at night was abrupt, compared with the rate of falling off in the late afternoon. It is known that the cracking of rubber depends upon both the concentration of ozone and the rate of air movement past the rubber strip. Since nighttime values of ozone at Beltsville are nearly zero except on windy nights and wind speeds tend to have a maximum soon after midday, it was supposed that the amount of rubber cracking in a strip exposed for 24 hours was a function of its exposure to ozone and wind speed during the 8-hour period between 0900 and 1700. The correlation between daily peak values and average values for this time span is fairly good (fig. 4). On October 4 and 5 the peak values occurred as relatively brief spikes, consistent with the high ratio of peak to average values. The ratios of peak to average 11-hour concentration (0900 to 2000) and to average 24-hour concentration (midnight to midnight) were found in approximate ratios 2:1 and 7:2, respectively, with somewhat more scatter.

When total crack depth and 8-hour ozone concentration at Beltsville are compared directly, little useful correlation is observed (fig. 5). The cluster of points at the lower right represents days of higher wind than the average. When ratios of total crack depth to average

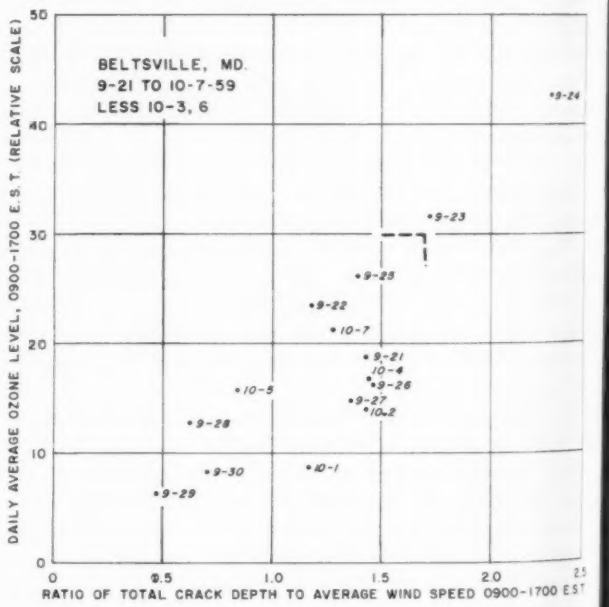

FIGURE 6.—Scattergram of ratio of total crack depth to average wind (0900–1700 EST) and the daily average ozone values (0900–1700 EST).

wind speed (0900–1700) are compared with average ozone levels, a reasonable correlation is found (fig. 6).

5. WIND SPEED CORRECTION

The wind speed used to correct for natural ventilation of the exposed rubber strips is the average of the speeds measured at Chantilly, Va. (site of Dulles International Airport) and Upper Marlboro, Md. (fig. 2). The anemometer heights are 20 and 30 feet, respectively. The speeds measured at the Washington National Airport were not included because of a change in anemometer height from 20 to 115 feet on September 30. The allowance for ventilation made in this paper is of course an approximation. Hence significance must not be given to small differences in the daily ratios of crack depth to wind speed. We shall consider only the highest ratios and the larger differences in the subsequent analysis.

6. COMPARISON OF 1958 AND 1959 RESULTS

We consider first the two high-ozone days September 23 and 24 and compare them with the 5 high-ozone days in 1958. The correspondence of the ensemble of weather parameters reported for the 1958 cases with the values of the weather parameters on these two dates is generally favorable. (See table 1). Light winds from the direction of the metropolis together with high solar irradiation are similar to 1958. Lower humidities in the tobacco field and higher temperatures at both tobacco field and airport are observed.

Severe weather fleck was observed at Beltsville on two days in 1959, July 27 and September 25. Physiological

TABLE 1.—*Some meteorological parameters on high-ozone days, 1958 and 1959, Beltsville, Md.*

Parameter	Range			
	5 days, 1958	9–23–59 1110 EST	9–24–59 1215 EST	7–26–59 1530 EST
At time of peak ozone level				
Temperature, tobacco field (° F.)	80–84	89	90	91
Temperature, airport* (° F.)	72–79	82	84	86
Relative humidity, tobacco field (percent)	54–66	34	27	----------
During 3-hr. period preceding peak				
Surface wind direction, airport*	SE to SSW	S	S	Calm, then S, SSW.
Surface wind speed, airport* (kt.)	3–8	5–7	7–8	0–6
Solar radiation, Silver Hill (langleys)	81–118	112	127	85
2 hours before peak				
Depth of convective layer (CL) (ft.)	200–4700	400	700	3600
Wind direction near top of CL	S to SSW	W to SSE	WSW to SW	SW
Wind speed near top of CL (kt.)	2–6	4	8	6
*Daily values, airport**				
Maximum temperature (° F.)	78–90	90	90	87
Average temperature (° F.)	66–78	77	77	80
Temperature range (° F.)	23–29	26	26	14
Precipitation on date, preceding date	0, 0	0, 0	0, 0	0, .01 in.

*Data measured at Washington National Airport, 14 mi. south-southwest of Beltsville.

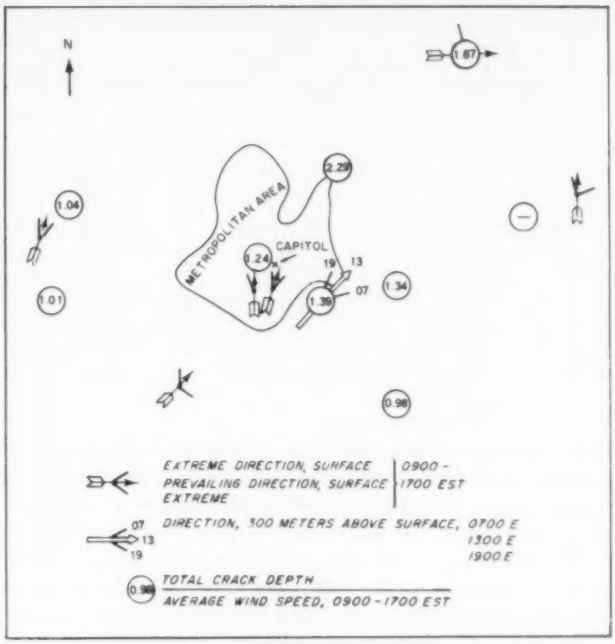

FIGURE 7.—Areal distribution of wind direction and total crack depth for the metropolitan and suburban areas of Washington, D.C. on September 24, 1960.

insult by ozone is presumed to have occurred the day before. The later date corresponds to the date of the highest peak ozone concentration in the period of recorder operations, September 24. The time of the peak value on July 26 is unknown, but if we take 1530, the correspondence of the weather ensemble is good (table 1). The differences from the 1958 experience on July 26 include higher air temperature, smaller temperature range, and the occurence of slight precipitation on the preceding day, none of which represents basic changes. The combined 1958 and 1959 results presented in table 1 should therefore form a basis for further analyses of high-ozone days near a metropolis and assist in the more difficult analyses of other days with less ozone but still higher ozone content than normal.

7. SOURCE OF OZONE

An examination of available ozone data and meteorological charts was made to ascertain the source of the high concentration of ozone observed on September 23 and 24 at Beltsville, Md. If ozone is produced by irradiation of city air with the proper concentration of nitrogen dioxide and hydrocarbons, then on days when light winds cross the city steadily and solar irradiation is high, we would expect an increase in rubber cracking on the downwind side of the city.

On September 24, a day of appropriate wind and irradiation, the results indicate that this was indeed the case (fig. 7). Most frequently reported surface wind direction

TABLE 2.—*Individual station and areal average values of the ratio of total crack depth to wind speed for September 15–30, 1959*

Date	Ratio of total crack depth to average wind speed									
September 1959	Central office	Beltsville	Centreville	Herndon	Baltimore	Davidsonville	Brandywine	Silver Hill	Upper Marlboro	Areal average
15		0.78	0.35							0.57
16		.97	1.20						0.45	.87
17		.49	1.25						.97	.90
18		.77	.75						.56	.69
19		.78	.67						.74	.73
20		1.50	.81						1.04	1.17
21		1.43	.65						1.16	1.08
22	1.19	1.18	1.60	1.67	1.15	2.18	0.75	1.46	1.21	1.38
23	1.08	1.72	1.28	1.17	1.66	1.34	1.05	1.44	1.42	1.33
24	1.24	2.29	1.01	1.04	1.87		.98	1.39	1.34	1.24
25		1.39	2.27	1.73	1.28		1.79	1.07	1.79	1.62
26		1.46	2.07	1.24	.89	1.36	1.34	.80	1.51	1.33
27		1.36	.53		2.33	1.67	.95	.88	.88	1.23
28		.62	.52		.67	.58	.92	.88	1.23	.77
29		.47	.81	1.31	.71	.60	.53	.69	.48	.70
30	.40	.70	.18	.28	.82	.58	.33	.97	.38	.52

and extremes during the period 0900 to 1700 EST, September 24, together with wind directions reported for 300 meters above sea level at Silver Hill, show a consistent flow from south or southwest across the metropolitan area. Flow from this octant will usually exclude Baltimore as a source region. Rubber-cracking ratio at Beltsville, downwind of the city, was 2.29, compared with 1.04, 1.01, and 0.98 upwind or crosswind at Herndon, Centreville, and Brandywine, respectively (see table 2). The Central Office and Baltimore strips were exposed 30 inches above roof tops, where wind speeds are known to be higher than at 30 inches above the ground. Hence the values 1.24 and 1.87 are probably both high. The relatively low value at the Central Office within the city might be ascribed to insufficient irradiation of the ozone precursor material in its travel from the outskirts of the metropolitan area to the south toward the site or to the presence of ozone sinks inside the city. A similar but less-pronounced gradient of rubber-cracking ratios was observed on September 23, the other high-ozone day.

An examination of the areal average of the rubber-cracking ratios (table 2) indicates that the background level of ozone began to rise significantly on September 20. A peak value of the ratio was reached on September 25, and a steady decrease until the end of the month followed. The steady rise in the ozone level may have been due to the advection of ozone-enriched tropospheric air over the area.

The source of the tropospheric air arriving over Washington during September 20 to 24 was determined from air trajectories on the 850-mb. surface. From the 20th to the 22d the trajectories indicated a polar source region in the vicinity of Hudson Bay, while the period from the 23d to the 24th indicated a source region over the eastern portion of the Gulf of Mexico. An inspection of the maximum wind charts indicated that while each of the air masses was in these source regions a jet stream axis was also present over the region. Unfortunately, measurements of the vertical distribution of ozone for these areas are not available for one to determine whether a downward transport of ozone from the stratosphere to the troposphere occurred during these periods. But previous experience [7] has indicated that such processes are possible near the jet stream axis. Investigations of the vertical velocities in the vicinity of jet streams [8,9] have shown that they may serve as a mechanism for carrying out vertical exchange processes in this region. Endlich [8] found that the strongest vertical speeds were located near the jet axis. Vertical speeds of 5 cm. sec.$^{-1}$ were seldom found farther than about 300 miles from the axis. Endlich and McLean [9], in a detailed analysis of the jet stream core based upon aircraft flights into the jet stream, reported that downward vertical speeds in excess of 1 m. sec.$^{-1}$ were at times encountered in the isotach centers of the jet.

Measurements of the vertical distribution of ozone in the vicinity of the jet axis were reported by Moreland [7]. The measurements were obtained during a series of intercomparison ozonesonde flights made at Denver, Colo., in April 1959. An example of an ascension made in the vicinity of the jet stream is shown in figure 8. The axis of the jet, 4 hours before release time, was located about 100 miles northwest of Denver (fig. 9). The aerological data (fig. 8) taken simultaneously with the ozonesonde ascent denoted a well-defined tropopause and a maximum wind speed of 40 m. sec.$^{-1}$ (78 kt.) at 11 km. The ozone concentration (ozone density) began a marked increase at about 9 km. indicating that the ozone had been injected into the troposphere from the stratosphere. In contrast, the vertical distribution of ozone shown in figure 10 was obtained when the jet stream was about 400 miles east of Denver (fig. 11). Under these conditions the ozone concentration did not begin its increase until 4 km. above the tropopause. Therefore preliminary evidence suggests that the injection of stratospheric ozone may occur in the vicinity of the jet stream axis.

8. CONCLUSIONS

Thus from all available evidence, which admittedly is meager, it appears that the occurrence of high ozone concentration in the Washington area may be the result

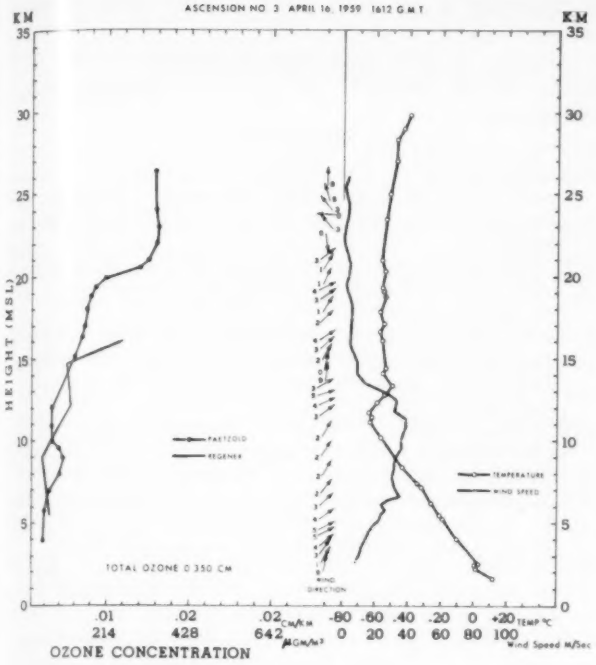

FIGURE 8.—Vertical distribution of ozone concentration, expressed in units of ozone density (cm./km. and micrograms/m.^{3}), and aerological data obtained in the vicinity of the jet stream axis.

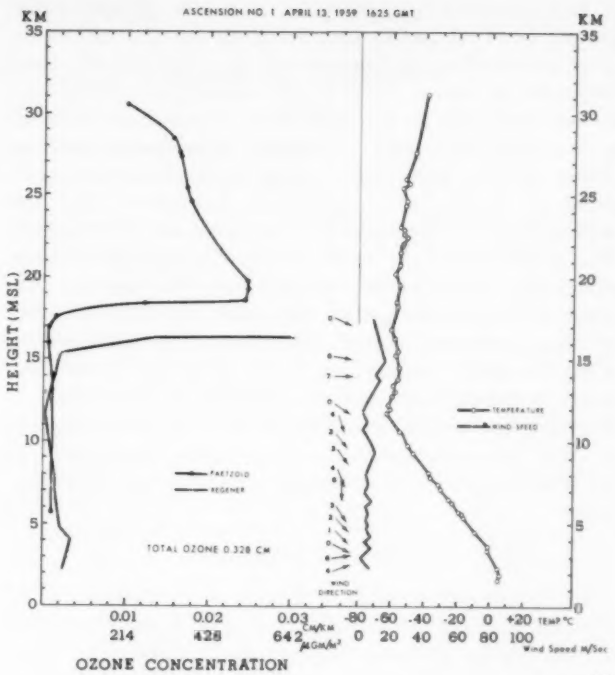

FIGURE 10.—Vertical distribution of ozone concentration, expressed in units of ozone density, and aerological data obtained in a region of low wind speed.

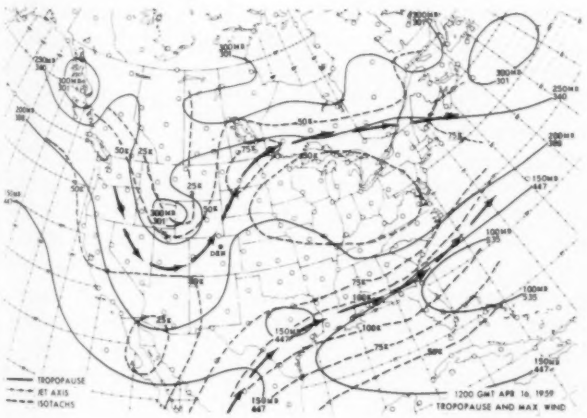

FIGURE 9.—Composite maximum wind speed (isotachs labeled in knots) and tropoause chart (contours labeled in hundreds of feet and millibars) synoptic 4 hours prior to ozonesonde ascension shown in figure 8.

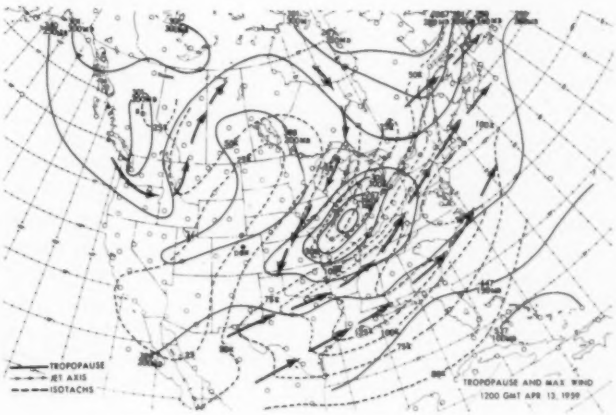

FIGURE 11.—Composite maximum wind speed and tropopause chart synoptic 4 hours prior to ozonesonde ascension shown in figure 10.

of two processes: (1) the increase of the general background level of ozone concentration by the advection of an enriched-ozone tropospheric air mass; (2) the local formation of ozone under stable atmospheric conditions at low levels due to the irradiation of precursor material as described previously. Evidence of an ozone gradient across the city with high concentration of surface ozone enhanced downwind supports the hypothesis that the metropolis is the dominant local source of ozone formation. The combination of these two processes may cause sufficiently high ozone concentration to produce the plant damage observed at Beltsville [2]. Whether one of these processes acting alone might be sufficient to cause the fleck damage cannot be determined with the amount of data now available. However, if more ozone observations become available, a more detailed analysis of the ozone-meteorological conditions conducive to plant damage and air-pollution potential can be undertaken.

ACKNOWLEDGMENTS

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CORRESPONDENCE

The Probing of the Tropopause by Balloons that Follow It—A Suggestion [1]

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Over a half century after the discovery of its existence, the tropopause is still one of the challenging mysteries to meteorologists. Radiosonde observations indicate that the vertical temperature gradient of the air often changes rather abruptly at the tropopause, although the apparent sharp break of the temperature gradient may be artificial because of the fact that straight line segments between reported temperature observations are employed to represent the true, and perhaps smoother, temperature distribution. Even if the kink of the temperature curve at the tropopause is removed, the fact remains that the temperature gradient changes rapidly within a rather narrow zone immediately above and below the point designated as the tropopause. The mystery about the tropopause is, therefore, not primarily its location, but rather the sharpness of the change of the temperature gradient that is associated with it. The radiative processes and the other large-scale heat transport processes that determine the mean atmospheric temperature distribution probably also determine the large-scale features of the tropopause, such as its general location and its seasonal and large-scale spatial variations. But what is the reason for the often observed sharp change of the temperature gradient at the tropopause? What are the physical processes that are responsible for its creation, maintenance, transformation, and destruction?

There are as yet no answers to these questions. Few suggestions concerning the creation of a sharp tropopause or its maintenance have been put forward (i.e. Möller [5], Staley [8], Kaplan [3]) and they are hypothetical in that they are based on other assumptions.

Still more basic and serious than this, it seems to this writer, is the fact that we do not even have an adequate observational study of the tropopause. We have only a gross and simplified picture of the tropopause and we do not know how a particular tropopause evolves with time.

There are several reasons why ordinary radiosonde observations fail to provide a detailed picture of the tropopause. First of all, the ordinary practice of reporting alternatively the humidity and temperature prohibits a continuous description of temperature. Second, as a result of the combined effect of the large ascensional rate of the balloon and the time lag of the sensing thermistor, the reported temperature actually represents an average temperature over a rather large distance in the vertical below the location of the reported temperature.[2] In addition, the representation of the temperature transmission in each baroswitch contact by a short trace on the recording paper often makes it undesirable to obtain more than one or two temperature readings in each baroswitch contact. At the 200-mb. level, which is about the level of the tropopause at middle latitudes, each contact represents a vertical distance of about 450 feet. Therefore, the maximum meaningful information that one may derive from the ordinary radiosonde is about one or two temperature readings for every 450 feet at the tropopause layer. This is not enough to delineate the detailed structure of the tropopause.

Equally as important as information about the detailed structure of the tropopause at one particular moment, is knowledge of the evolution of the same tropopause with time. Efforts to follow the life history of a tropopause have met with little success due to the fact that the observations now available at fixed locations are not meant and are not suitable for this kind of study. Only by following and making observations of one and the same tropopause, can the life history of the tropopause be ascertained.

In view of the above inadequacies of the present radiosonde system, it is hereby suggested that instrumented constant level balloons be employed to follow and to probe the tropopause. This suggestion was prompted by the following two observations:

1. At both low and high latitudes the tropopause is often well defined and coincides with the minimum temperature. It seems, therefore, that the tropopause is a continuous surface of minimum temperature with considerable horizontal extent at those latitudes.

2. In the last decade or so, constant level balloons have been successfully used to probe the air flow of upper troposphere or lower stratosphere (Moore, Smith, and Gaalswyk [6], Neiburger and Angell [7]). The balloons were set to float along a certain isobaric surface.

If the tropopause is a surface of minimum temperature, then in principle it should be possible to set the balloons to stay and to float at this surface of minimum temperature. This can be done, for example, by having a series of simultaneous temperature observations (3 or more) from thermistors attached an equal distance apart on a line dangling from the balloon, and by having the floating level of the balloon regulated by the requirement that the middle thermistor should register the minimum temperature.[3] If due to the ascending or descending of

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[1] This correspondence is an abridged and revised version of a scientific report [1] of the same title written under Contract AF19(604)-6146 sponsored by Geophysics Research Directorate, Air Research and Development Command.

[2] For one type of U.S. radiosonde, the vertical distance of averaging is estimated to be no less than 350 feet (Chiu [1]).

[3] Since the balloon package is floating with the air, an aspirator would be necessary to keep each of the temperature sensing elements ventilated in order to prevent radiation errors.

the balloons this requirement is not met, then the comparison between the temperature registered by the middle thermistor and its immediate neighboring thermistors will set a mechanism into operation (e.g., the dropping of the ballast or the releasing of the gas from the balloon) to bring the balloon up or down to the desired level. In this manner it should be possible to control the balloon, causing it to float and to oscillate about the tropopause with a certain preset limit (this limit is determined by the spacing between the thermistors and by the sensitivity of the height control mechanism).

The above described observations, if successful, could provide us with a detailed temperature structure of the tropopause layer (a tropopause layer is here interpreted as meaning a layer of certain thickness in which the tropopause is found).[4] There are many other useful pieces of information which we should like to have. For example, if the humidity can be measured with certain desired accuracy then we may replace all the thermistors in the above experiment by humidity elements and get a detailed structure of the vertical humidity distribution. The importance of this kind of information is obvious. The difficulty is, of course, whether equipment can be found which will measure the humidity with adequate accuracy at the tropopause level.

Another very useful piece of information that might be obtained from the floating balloons is the heating or cooling of air in the tropopause layer by radiative processes. This may be done, for example, by installing three of Suomi's [9] net radiometers at, above, and below the tropopause. From these measurements the divergence of radiative flux, and therefore the temperature change, above and below the tropopause could be easily calculated. In this way it might be possible to see just how the radiative processes are affecting the detailed structure of the tropopause, providing that the balloons are traveling with the same air parcel.

It is also possible that the radiation measurements at the tropopause may be used to settle one of the very important questions about the tropopause; i.e., is the tropopause a material surface?[5] By material surface is meant one consisting of the same air particles as time progresses. If the tropopause is a material surface and the ballon follows the horizontal motion of the air, then the balloon will stay in the same parcel of air as it travels. In that case there should be no advection of heat into the temperature sensing elements. The change of the potential temperature registered by the thermistors would then be mainly due to radiative processes. By comparing the measured potential temperature changes from the radiometers, on the one hand, and those from the thermistors, on the other, it should be possible then to ascertain whether or not the tropopause is a material surface.

An alternate scheme of carrying out the observation is to set the balloon to float freely near the tropopause. This scheme was suggested to the writer by the Air Force balloon design and operation groups at Geophysics Research Directorate, Bedford, Mass., when they were consulted on the balloon flight problem. According to three people [10], "the balloon could support a line about 2,000 feet long beneath it, with thermistors spaced at appropriate intervals along the line. The balloon could be set to float at or just below the expected height of the tropopause, and its altitude could be adjusted upward in small increments by the dropping of ballast." In this way, there is a fair chance that the line dangling from the balloon will traverse the tropopause.

At this stage, the suggested new technique of observing the tropopause is only an idea. Funds for its experimentation must be acquired. Much effort then must be made to design and develop the balloon and its instrumentation and to test them in flights. Only after many flight tests can one begin to assess its usefulness. But in view of our meager knowledge about the tropopause, if this correspondence can serve in any way to stimulate interest and effort into the research of the tropopause, then it already has served a very useful purpose.

ACKNOWLEDGMENTS

Thanks are due to those, too numerous to list individually, who read and commented on the original versions of this paper.

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[4] According to the people at Instrument Research Laboratory, Geophysics Research Directorate, Bedford, Mass., an encoder-thermistor arrangement is now available that permits up to 25 temperature readings on a 2,000-foot line.

[5] In the literature, opinions both for and against the idea of a material tropopause have been expressed (Lowell [4], Danielsen [2]).

THE WEATHER AND CIRCULATION OF MAY 1961

Persistent Cool Weather in the United States

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1. HIGHLIGHTS

The outstanding feature of the weather of May 1961 was the persistence of the cold regime of the preceding month [1] throughout most of the United States east of the Rocky Mountains and also in the Pacific Northwest. In the East numerous stations from St. Louis, Mo., eastward through the Ohio Valley to Youngstown, Ohio reported the coldest average temperatures on record for May. In the Far West unseasonably cold temperatures retarded the maturity of crops through most of the Great Valley of California and below normal temperatures extended into extreme southern California.

A major contribution to the low mean temperatures for May came from an extremely cold polar air mass that blanketed the eastern half of the country during the last week of the month. Beginning on the 26th, record low temperatures were recorded throughout the Middle West and eastward, with frost as far south as Kentucky and snow in Ohio and Michigan. Daily temperature anomalies ranged from more than 20° F. below normal in New England and the Mid-West to 10° F. below normal through the Gulf States during this period.

Extremely heavy precipitation from the Central Plains eastward through the Ohio Valley resulted in major floods throughout the month in most of the Arkansas, Missouri, Ohio, and Middle Mississippi River watersheds where amounts ranged from more than 8 inches at Concordia, Kans. to a record 12.22 inches at Evansville, Ind. On the other hand, drought conditions that prevailed in April 1961 through the Southwest from Texas to southern California continued during May except in extreme western Texas. There was no measurable precipitation in the extreme Southwest or at Corpus Christi, Tex., a new record for May at that station.

2. THE GENERAL CIRCULATION

The general circulation for May 1961 at 700 mb. (fig. 1) does not show many unusual features in spite of the extremely anomalous weather observed over most of the United States. Blocking, which had dominated eastern Canada during April [1] and the northeastern Atlantic during March [2], retrograded rapidly to the Alaskan area where mean height anomalies increased 210 ft. from April (fig. 2). At the same time height anomalies decreased by 570 ft. near Baffin Island, representing a rather abrupt return to normal in that area.

In the Southwest Pacific filling of the deep Asiatic coastal trough observed in April and intensification of the subtropical High downstream were predominantly climatological as shown by the small anomalous changes (fig. 2). However, this normal change, concurrent with deepening east of Kamchatka and blocking to the north, produced a zone of confluence south of Kamchatka which was the dominant feature of the circulation. Figure 3 shows that the maximum mean 700-mb. westerlies in this region were from 4° to 5° of latitude north of their normal position (A) and 9 meters per second faster than normal (B). Downstream, the effects of blocking on this high-index Pacific circulation are shown by a diminution of wind speeds in the broad difluent area of western North America and by the southward displacement (from normal) of the 700-mb. jet stream through the extreme southwestern United States.

Elsewhere the anomalies of the general circulation were within 160 ft. of the long-period normal, the largest month-to-month changes (fig. 2) being indicative of a return to normal from the more anomalous state of April [1].

3. TEMPERATURE

The cool temperature regime of April continued through May with nearly all of the contiguous United States averaging below normal except Texas and the Rocky Mountain States (fig. 4). In much of the Mid-West and Ohio Valley the persistent low temperatures of April and May 1961 combined to make this period the coldest since 1907. The cool regime in the Pacific States and the Great Basin, while not of record intensity, was extremely persistent, particularly in the Great Valley of southern California. The number of days in the month during which the average daily temperature exceeded the normal ranged from only six at Sacramento to four at San Diego. Santa Maria recorded only one day above normal and that by only 1° F.

The unusual month-to-month persistence of temperature

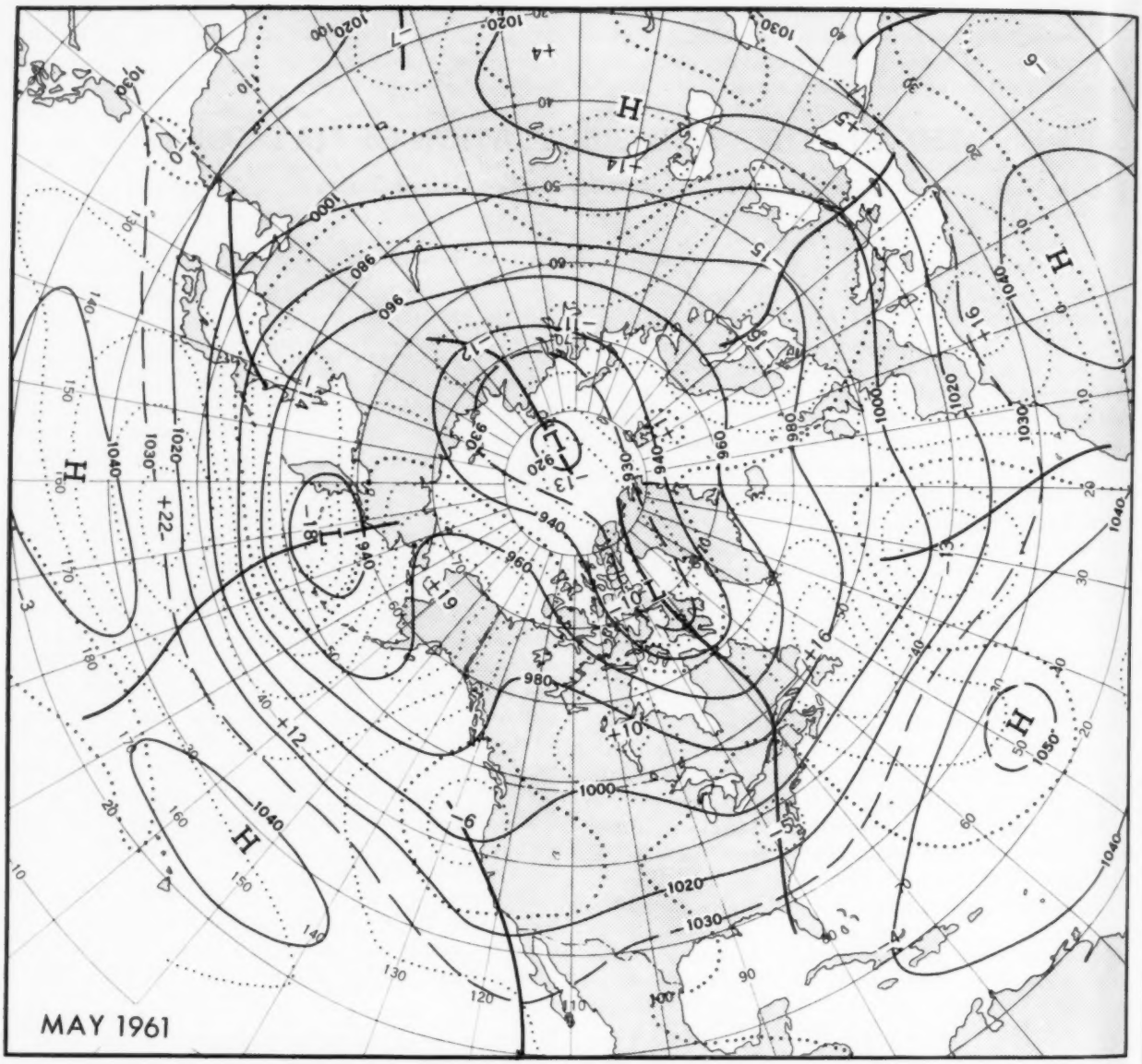


FIGURE 1.—Mean 700-mb. contours (solid) and height departures from normal (dotted) (both in tens of feet) for May 1961. Above normal heights in Canada and Alaska were associated with frequent anticyclogenesis and cool weather east of the Rocky Mountains.

is well illustrated by figure 5, the change in temperature anomaly class (out of five classes) from April to May. In a distribution of 100 cities, 37 remained in exactly the same class as the previous month, covering the area shown by crosshatching. No city changed by as many as 3 or 4 classes, and 79 changed by no more than 1 class. The latter figure compares with 59 expected by chance, 32 observed from March to April 1961 [1], and 62 for the average April–May change from 1942 to 1957 [4].

Although the pattern of temperature anomaly follows closely the negative height anomaly at 700 mb. the relative magnitude of the temperature anomaly was much greater than that of the height anomaly. Examination of the 15-day components of the monthly 700-mb. height mean, figure 6, shows a two-fold effect operating to maintain cool temperatures in the Far West. During the first half of the month low temperatures were associated with anomalous northerly flow from a blocking High centered over Alaska (fig. 6A), and with the main westerlies displaced well south of 40° N. During the latter half of the

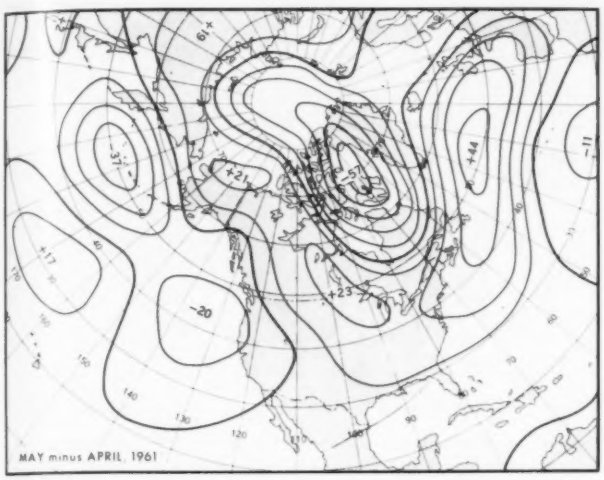


FIGURE 2.—Change in 700-mb. height anomalies (tens of feet) from April 1961 to May 1961. Relaxation of blocking in eastern Canada is represented by the largest change area.

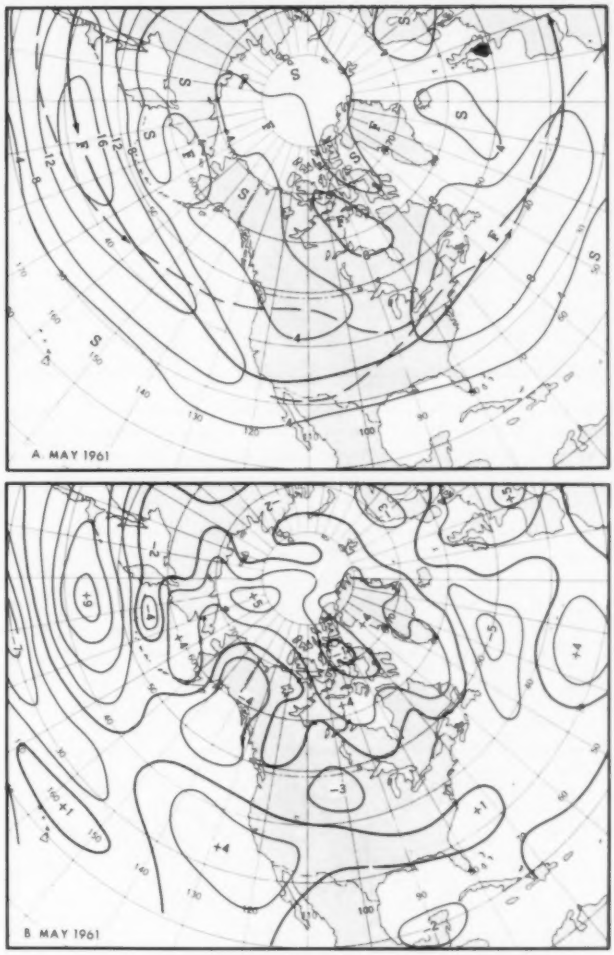


FIGURE 3.—(A) Mean 700-mb. isotachs and (B) departure from normal wind speed (both in meters per second) for May 1961. Solid arrows in (A) indicate primary axes of the westerly jet stream, and dashed arrows indicate their normal May positions. The westerlies were displaced well south of the normal position over western United States, and an important secondary maximum was located over northeastern Canada.

month temperatures modified considerably in the Northwest (fig. 8 C, E) as the blocking over Alaska relaxed (fig. 7), and the circulation returned to the dominant spring pattern of troughs near the east and west coasts and a strong full-latitude ridge through mid-continent (fig. 6B). The extreme negative tilt (northwest to southeast) of the west coast trough is commonly associated with the southward displacement of mid-latitude westerlies and helped maintain cool temperatures in southern California.

In contrast to the persistent temperature regime of the Far West, temperatures east of the Continental Divide, although predominantly below normal, showed more variability (fig. 8). This variability can be related to the differences in the 700-mb. bimonthly circulations (fig. 7).

During the first half of the month most of the United States was dominated by a broad cyclonic circulation augmented by strong northerly flow in western Canada associated with a blocking High over Alaska. Following an initial outbreak of cold air which affected most of the country except the Gulf States, succeeding polar air masses followed a more northerly track with a warming trend east of the trough in central United States. The track of the "glancing Highs" associated with these shallow polar outbreaks is shown in figure 9A by the arrows through the Great Lakes and eastern Canada. Examination of the 5-day mean charts shows a transition period near mid-month during which the maximum-curvature trough in central Canada joined with the shallow trough in the Northern Plains (fig. 6A) to form a full-latitude trough near the east coast, and the blocking High over Alaska moved east to form a full-latitude ridge just east of the Continental Divide (fig. 6B). Associated with the development of this large-amplitude trough and ridge system was rapid warming throughout the mountain area of western North America (fig. 8G). A succession of cold polar anticyclones moved into the eastern half of the country, as shown by the southernmost track in figure 9A, resulting in frost and light snow in the Mid-West and record low minimum temperatures throughout the East.

4. PRECIPITATION

Of particular interest is the unusually heavy precipitation which occurred in the Central Plains and Middle Mississippi watershed and resulted in floods throughout the area most of the month (fig. 10). Heaviest rains fell during the first half of the month (fig. 8 B, D) associated

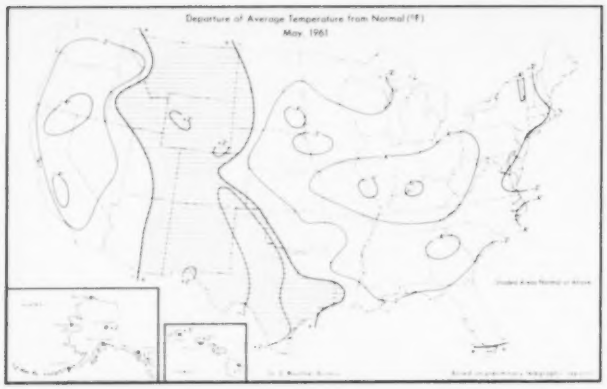


FIGURE 4.—Departure of average surface temperature (° F.) from normal for May 1961. (From [3].) Temperature averaged above normal (shaded) in the Rocky Mountain area but below normal in the remainder of the nation.

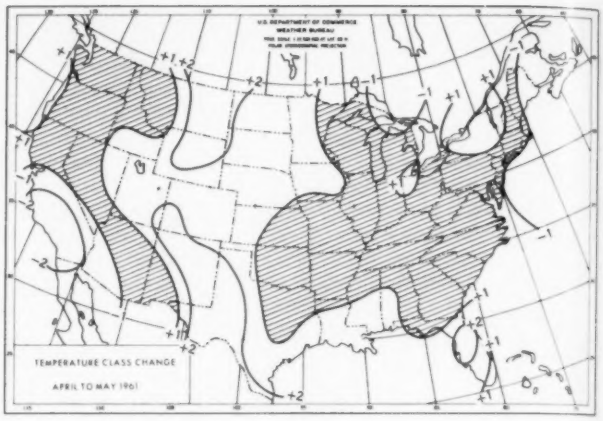
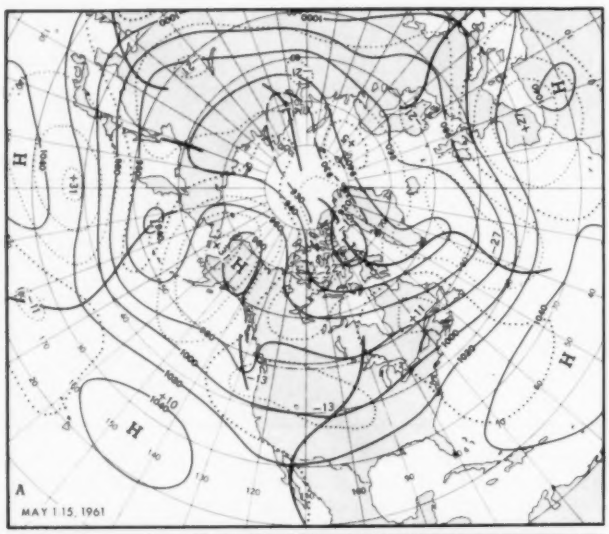


FIGURE 5.—The number of classes (out of five) the surface temperature anomaly changed from April to May 1961. The hatched area represents the area of no change.



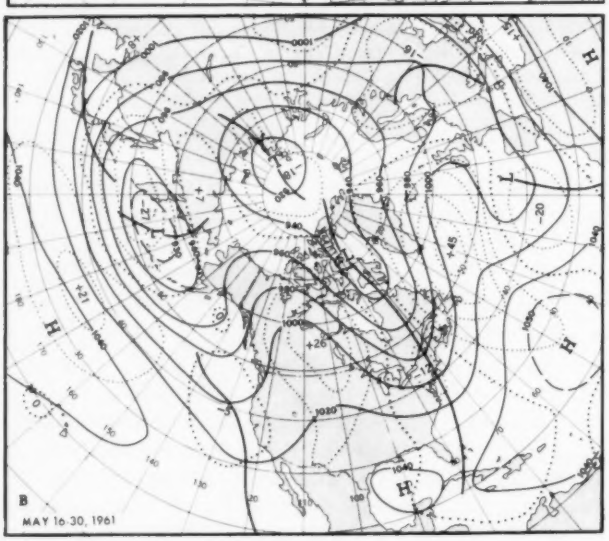


FIGURE 6.—Fifteen-day mean 700-mb. height contours and departures from normal (both in tens of feet) for (A) May 1–15, 1961, and (B) May 16–30, 1961.

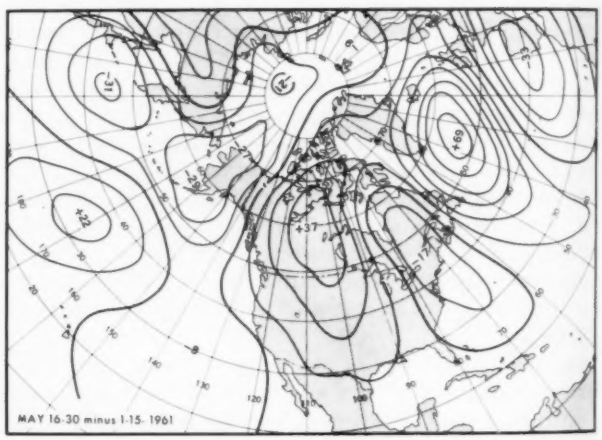


FIGURE 7.—Change in 15-day mean 700-mb. height anomaly from May 1–15 to May 16–30, 1961, in tens of feet. Large intramonthly changes occurred over most of North America except the west coast of United States.

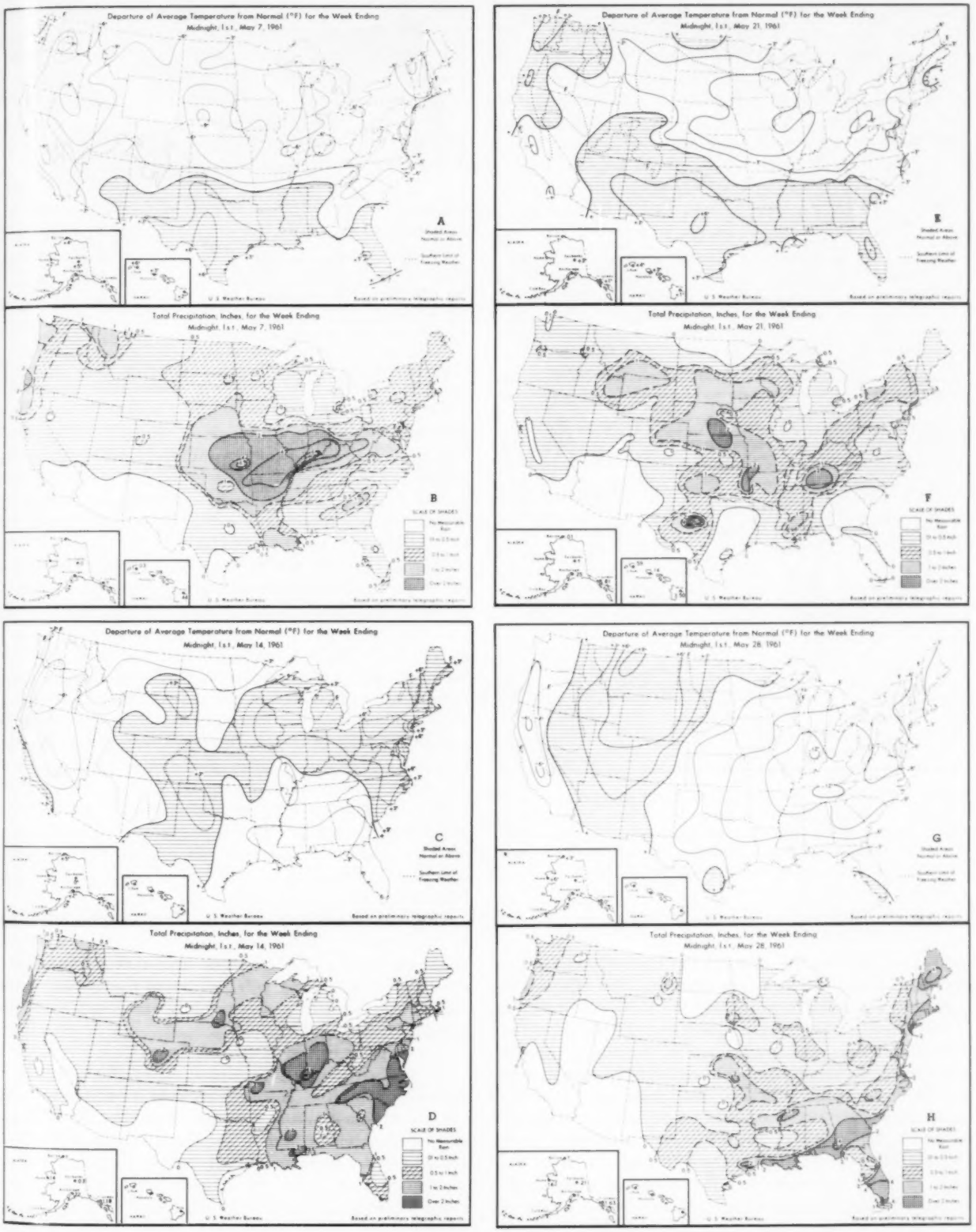

Departure of Average Temperature from Normal (°F) for the Week Ending
Midnight, l.s.t., May 7, 1961
A
Total Precipitation, Inches, for the Week Ending
Midnight, l.s.t., May 7, 1961
B
Departure of Average Temperature from Normal (°F) for the Week Ending
Midnight, l.s.t., May 21, 1961
E
Total Precipitation, Inches, for the Week Ending
Midnight, l.s.t., May 21, 1961
F
Departure of Average Temperature from Normal (°F) for the Week Ending
Midnight, l.s.t., May 14, 1961
C
Total Precipitation, Inches, for the Week Ending
Midnight, l.s.t., May 14, 1961
D
Departure of Average Temperature from Normal (°F) for the Week Ending
Midnight, l.s.t., May 28, 1961
G
Total Precipitation, Inches, for the Week Ending
Midnight, l.s.t., May 28, 1961
H

FIGURE 8.—Departure of average surface temperaure from normal (° F.) and total precipitation (inches) for the weekly periods ending (A,B) May 7, (C,D) May 14, (E,F) May 21, and (G,H) May 28, 1961. (From [6].)

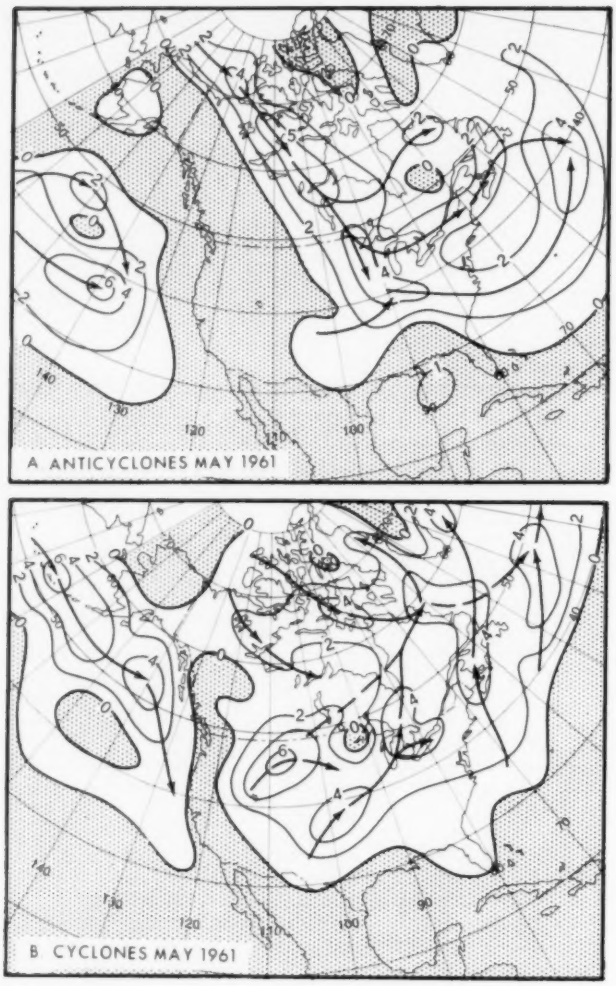


FIGURE 9.—Frequency of (A) anticyclone and (B) cyclone passages (within 5° squares at 45° N.) during May 1961. Primary tracks are indicated by solid arrows, secondary tracks by dashed arrows. Frequent weak Lows in the Northern Plains were of secondary importance compared to major storm development in Central Plains.

with the shallow trough through the Plains States and the depressed axis of prevailing westerlies. The effect of the depressed westerlies in restricting the northward intrusion of Gulf moisture is shown indirectly in the frequency and prevailing tracks of daily cyclones for the month (fig. 9B). Although a maximum number of closed Lows was observed in the northwestern Plains, few developed into well organized cyclonic systems, while the major developments occurred just north of the prevailing westerlies in the Central Plains. An interesting effect of the northward limit of Gulf moisture was the range of precipitation through Indiana from a record 12.22 inches at Evansville in the south to only 1.19 inches at South Bend in the north, the dryest there since 1939. Such sharp gradients are

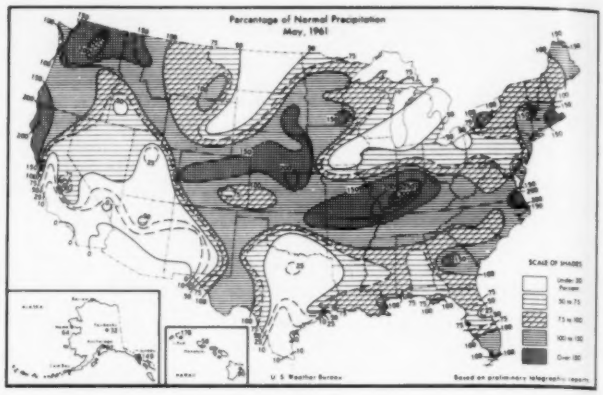


FIGURE 10.—Percentage of normal percipitation for May 1961. (From [3].) No measurable precipitation in parts of the Southwest contrasted with above normal amounts in many other areas.

frequently associated with marked confluence of the mean 700-mb. contours, such as prevailed over Indiana this month (fig. 1). Precipitation was normal to above normal in the Pacific Northwest under the influence of the weak coastal trough despite the weakness (relative to normal) of the westerlies at mid-latitudes.

During the week ending May 15, a major storm moved out of the lower Mississippi Valley and produced moderate to heavy precipitation over most of the eastern half of the country. Intense deepening of the parent storm as it moved into eastern Canada resulted in a fresh polar outbreak of cold air reaching to the Gulf States, and a rather intense wave developed in response to the sharp temperature gradient near northern Florida. However, a sudden northward shift of the jet stream in response to the deep cyclonic vortex near Hudson Bay and anticyclogenesis to the south over the Great Lakes resulted in cutting off the wave near Florida from the main westerlies. The major portion of the month's precipitation in the coastal area of South Carolina to Virginia was produced by the slow northward migration of this cut-off coastal Low from May 10 to May 13.

Heaviest precipitation in the Northeast occurred late in the month in conjunction with wave development as a cold front moved off the Middle Atlantic coast in advance of the extremely cold polar air mass mentioned earlier. Subsequent baroclinic deepening in the mean east coast trough resulted in precipitation amounts in excess of 4 inches in parts of New England (fig. 8H).

As is often the case, precipitation, or the lack of it, is difficult to specify. In the Southwest it seems likely that the strong low-latitude westerlies operated to produce a rain shadow effect and to prevent moisture from being introduced by large-scale southeasterly components of the general circulation. More difficult to explain is the continued drought in eastern Texas. Here lack of moisture at high levels and anticyclonic vorticity just south of the jet stream limited precipitation to scattered showers

through most of the period. During the latter half of the month a strong easterly flow at low levels associated with a series of large polar anticyclones moving along the southern track of figure 9A resulted in a considerable amount of up-slope precipitation in western Texas. An interesting note on the discontinuous nature of precipitation is the difference between the monthly totals at Houston, Tex. of 0.63 inches at the city office and 3.59 inches at the Airport Station.

In an effort to specify more clearly the month's precipitation, a study was made of the 600-mb. vertical motion charts as computed twice daily from the baroclinic model currently used by the Numerical Weather Prediction Branch (NWP). Values were read at 5° intervals of latitude and longitude, and charts were constructed of weekly mean values and mean positive values only for periods corresponding to those in figure 8, and mean values and mean positive values only for the period corresponding to figure 10. The results show little correspondence between the observed precipitation patterns and the patterns of *mean* values of vertical motion on either a weekly or a monthly basis. On the other hand, the patterns of *positive* values only show a fair correspondence with the observed precipitation in some areas. However, there are many inconsistencies; e.g., the dry areas of Texas and the Great Lakes show definite maxima in several cases, and the heavy rains in the Ohio Valley and New England lie in areas of minimum vertical motion in others. This would indicate that other parameters such as available moisture, warm air advection, thickness advection, the extent of over-running of a cold stable air mass, etc., should be included in any specification scheme. Unfortunately the measurement and data processing of these parameters is not as easy as for vertical motion.

This experiment is similar to that done by Woffinden [5], and was repeated only because of the difference in the circulation and weather regime. However, the general results and conclusions are the same.

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